286500-5-T

Requirements Definition Report

Variable Dynamic Testbed Vehicle

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FEBRUARY 1997

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Contract Number 959915

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TECHNICAL REPORT STANDARD TITLE PAGE

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
286500-5-T		

4. Title and Subtitle	5. Report Date
Variable Dynamic Testbed Vehicle Requirements Definition Report	February 1997
	6. Performing Organization Code
Author(s)	8. Performing Organization Report No.
D.R. McLellan, T.J. Blessing, J.L. Nyman	286500-5-T
9. Performing Organization Name and Address	10. Work Unit No.
Environmental Research Institute of Michigan P.O. Box 134001 Ann Arbor, MI 481134001	11. Contract or Grant No. 959915
12. Sponsoring Agency Name and Address	13. Type of Report and Period Covered Technical December 1996 to Feb. 1997
Jet Propulsion Laboratory 4800 Oak Grove Drive Pasadena, CA 91109	14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

The material in this document forms the Requirements Definition Report for development of the Variable Dynamic Testbed Vehicle (VDTV) This effort is in support of the Jet Propulsion Laboratory (JPL) VDTV Implementation Task. We are designing, developing, fabricating, integrating, testing, and delivering a VDTV in compliance with the requirements set forth by JPL. To produce the Requirements Definition Report, we have performed the following task items: conducted trade studies based on JPL requirements to validate the proposed approach for the base vehicle; conducted a comprehensive dynamics analysis of the selected design concept to confirm the expected performance capability range; addressed the cost, schedule, and technical feasibility of providing backup to the dynamic subsystems to provide fail-safe operation in the case of a malfunction of a safety-critical component; conducted analyses to evaluate JPL's requirements that pertain to the dynamic characterization of the VDTV; defined interface requirements for all elements of the delivered system, and defmed system test requirements.

17. Key Words	18. Distribution Statement
variable dynamic testbed vehicle, VDTV, dynamic subsystems, safety-critical, trade studies, dynamics analysis	Limited availability. Further distribution of this document available only through the Jet Propulsion Laboratory.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Pricc
unclassified	unclassified	160	

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1.0 RECOMMENDATIONS FOR VEHICLE EMULATION RANGES BASED ON THE FLEET DATA

Handling metrics of the U.S. passenger car fleet were obtained from NHTSA, General Motors and Ford. The NHTSA data is the oldest, representing cars that were built from 1977 to 1989. The GM data was in summary form only and represented the passenger car fleet of the early to mid 1980s. The Ford data was the most recent (1995 model year) and the most complete. Two important findings with respect to the VDTV requirements detailed in JPL's Exhibit I follow.

1. From Exhibit I, the range of understeer gradient for the VDTV is called out as -4 to +13 deg/g at 0.15 g. The range of understeer gradient (deg/g) based on all the fleet data taken together + or - 25% is 0.315 to 8.125 deg/g (Chart 1-2). This is as high as 8.125 deg/g only because of an outlier at 6.5 deg/g, as the 3 sigma upper bound is only 5.92 deg/g. The lower bound is also driven by an outlier at 0.4 deg/g, putting the lower bound -25% at 0.315 deg/g. The 3 sigma lower bound of -0.67 deg/g is not meaningful as there are no passenger cars that have linear range oversteer.

NHTSA, JPL, ERIM, and MBA need to discuss the observed range of understeer gradient in terms of NHTSA's objectives with the VDTV. ERIM recommends reducing the range to 0.3 to 6.5 deg/g.This captures the low observed point -25%.If the singular point at 6.5 deg/g that is driving the upper bound is ignored, the rest of the data +25% is captured below 6.25 deg/g. Thus an upper limit of 6.5 deg/g would still capture the singularity and fully represent the rest of the data.

ERIM also recommends reviewing the understeer gradient for V.S. lateral acceleration that is called out in Exhibit I, Figure 3.5 (page 17). The emulation range called for contains unstable regions. By the time of our meeting on December 5, 1996, ERIM will be able to document the effect of extreme values of understeer and oversteer on the behavior of a passenger automobile. It is significant that the fleet is contained in this narrow bound.

2. From Exhibit I, the range of roll gradient called out for the VDTV is -2.5 to -12.5 deg/g. The roll gradient of modem cars (based on the Ford data) + or - 25% is -2 to -9.25 deg/g The N-year-old GM data indicates a single car with a roll gradient of -11.3 deg/g. This is extremely high and does not seem to be characteristic of the modem fleet. ERIM recommends using the more modem Ford fleet-derived data and limiting the roll **gradient to no more than 10 deg/g**. A car can be allowed to roll excessively only if its roll gradient is very nonlinear or if its lateral acceleration limit is low. Once the car body rolls on to its suspension compression bumpers, the directional handling control achieved by load transfer distribution is lost.

The rest of the Exhibit I requirements appear to be a reflection of the modem fleet.

The data on steering parameters, frequency bandwidth, and handling overshoot will be valuable as we develop our emulation parameters for small, medium, and large cars. .

The following 19 charts cover the metric analysis performed.

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Chart 1-1. **SUMMARY OF GOALS, REQUIREMENTS AND ANALYSIS RESULTS**

Handling Metric	Goal per Fleet Data	Requirement per RFP	Analysis Result per Simulations	Feedback Parameters
Understeer Gradient, deg/g @ 0.15g	-0.7 to +9.0	-4 to +13	-.16 to +9.0 -.95 to +10	Sideslip, Lat. Acc. (75 mph) Yaw Rate/Lat. Acc (40 mph)
Roll Gradient, deg/g	-12.5 to -1	-12.5 to -2.5	(see Delphi Anal.)	
Sideslip Angle Gradient, deg/g -50 mph	-5 to +l	NA	-5 to +4	Yaw Rate, Sideslip (75 mph)
Steering Torque Gradient, in-lbf/in	50 to 300	Specified in Terms of % Power Assist		
Steering Torsional Stiffness, in-lbf/deg	0.3 @ 30 mph to 3.5 @ 75 mph	NA	-------	
Maximum Lateral Acceleration, g	0.4 to 1.0	0 to 0.95g on 30m Circle	(see MDI anal.)	
Steering Sensitivity, g per 100 deg, S WA Angle	4 to 1.5* @ 45 mph 4 to 2.2* @ 60 mph 4 to 2.4* @ 75 mph	NA	Fully Variable, Limited by Max. Steer Angle	Steering Wheel Angle
Lateral Accel. -3db Bandwidth, hz	6 to 2.0 @ 60 mph	NA	No Frequency Responses	
Lateral Accel. 90% Rise Time, sec 0.15g, 80 km/hr	NA	0.2 to 0.9	I.22 to 0.89	Sideslip Rate, Yaw Accel.
Yaw Rate Band -3db Bandwidth, hz	1.5 to 4.0 @ 25 mph 0.7 to 3.0 @ 50 mph	NA	-------	
Percent Overshoot in Yaw Rate	0 to 40% (50mph) 0 to 100%' (75 mph)	NA	2% to 58%	Yaw Accel.
Time to Peak Yaw Rate Response, sec (.4g, 50 mph)	0.2 to 0.9	NA	0.22 to 0.89	Sideslip Rate, Yaw Accel.
Roll Angle Bandwidth, hz	0.8 to 4.8 (25 mph) 1.3 to 1.5 (50 mph)	NA	No Freq. Resp.	

* Maximum value increases with decreasing understeer gradient, e.g., infinite for oversteer, above critical speed.
# Corresponds to high understeer gradient and low damping.

Chart 1-2. ***Understeer Gradient vs. Vehicle Weight***

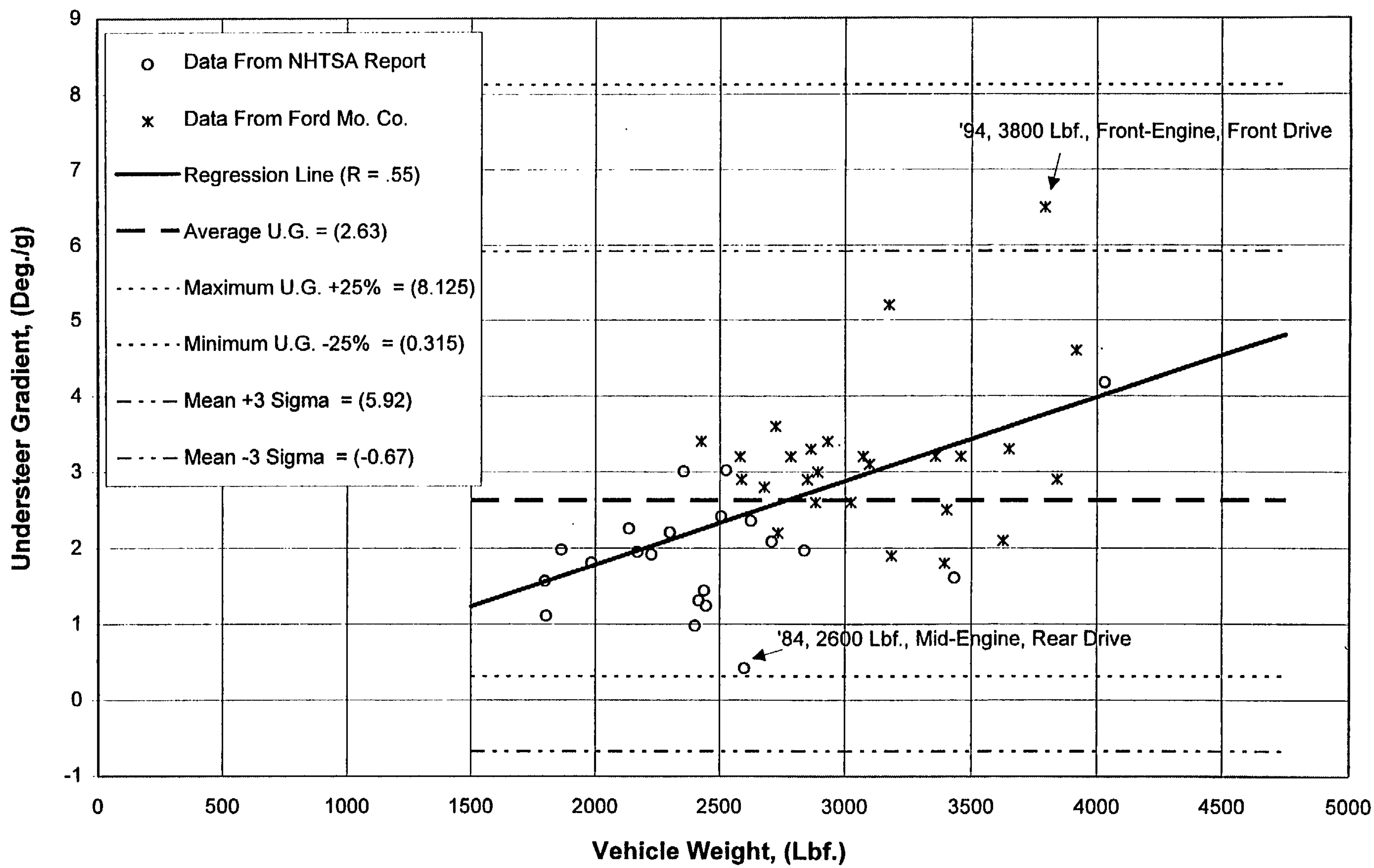

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Chart 1-3. ***Summary of Understeer Gradient Data***

Units for U.G. - Deg./g

	Corn bined	Ford	NHTSA	GM Report
Mean Understeer Gradient	2.63	3.18	1.95	3.2
Max Understeer Gradient	6.5	6.5	4.18	7
Min. Understeer Gradient	0.42	1.8	0 42	0.7
Max + 25% U.G.	8.125	8.125	5.225	8.75
Min. -25% U.G.	0.315	1.35	0.315	0.525
Std. Deviation	1.099	0.993	0.814	-
Mean +3Sig. U.G.	5.92	6.16	4.39	
Mean -3Sig. U.G.	-0.67	0.20	-0.50	-
Veh. Production Year Range		'93 - '96	'77 - '89	'80 - '87

Ford Motor Company: Janet S. Basas Research Engineer,
Vehicle Dynamics Test Vehicle Dynamics Attributes Engineering,
Advanced Vehicle Technology

Transportation Research Center. Inc.: Gary S. Heydinger, Ph. D., Vehicle Dynamics Simulation and Metric Computation for Comparison With Accident Data. (Report Number: DOT HS 807 828). March, 1991

General Motors; Dennis T. Kunkel & Ronald L. Leffert, Objective Directional Response Testing, May 8. 198T

Chart l-4. Metric Analysis, of Understeer Gradient

Vehicle Number	Where Was Data Obtained	Year	Make	Model 1	Curb/Test Weight, Lbf.
1	NHTSA	1977	Renault	LeCar	***1799***
2	NHTSA	1982	Toyota	Starlet	1804
3	NHTSA	1984	Honda	CRX	1864
4	NHTSA	1984	Honda	Civic HB	1984
5	NHTSA	1982	Honda	Civic 4dr	2224
6	NHTSA	1983	Nissan	Sentra	2353
7	NHTSA	1980	Chevrolet	Chevette	2299
8	NHTSA	1983	Volkswagen	Jetta	2135
9	NHTSA	1983	Dodge	Omni	2169
10	NHTSA	***1987***	Datsun	510	2400
11	NHTSA	***1982***	B.M.W	320i	2415
12	NHTSA	***1987***	Hyundai	Excel	2438
13	NHTSA	***1983***	Toyota	Camry	2446
14	NHTSA	***1985***	Nissan	Stanza 4dr	2505
15	NHTSA	***1985***	Chevrolet	Cavalier	2525
16	NHTSA	***1989***	Ford	Escort	***2708***
17	NHTSA	***1980***	Datsun	2oosx	2626
18	NHTSA	***1984***	Pontiac	Fiero	2601
15	NHTSA	***1985***	Oldsmobile	Ciera	2838
20	NHTSA	***1987***	Ford	Tbird	3430
21	NHTSA	***1980***	Buick	LeSabre	4030
22	FORD	***1996***			3183
23	FORD	***1996***			3096
24	FORD	***1996***			3392
25	FORD	***1996***			3356
26	FORD	***1995***			3649
27	FORD	***1994***			***3794***
28	FORD	***1995***			3625
30	FORD	***1995***			2891
31	FORD	***1995***			3022
32	FORD	***1994***			2850
33	FORD	***1996***			3401
34	FORD	***1993***			3071
35	FORD	***1994***			***3917***
36	FORD	***1995***			3841
37	FORD	***1994***			2931
38	FORD	***1994***			***3457***
39	FORD	***1994***			2424
40 .	FORD	***1995***			***2734***
41	FORD	1995			***3174***
42	FORD	1994			2582
43	FORD	1996			2883
44	FORD	1995			***2679***
45	FORD	1994			2864
46	FORD	1994			2784
47	FORD	1994			2588
48	FORD	1994			2724
25	FORD	1994			4497

Chart l-5. Summary of Roll Gradient Data

	Ford Provided Data	GM Report
Mean Roll Gradient, Deg/g	4.77	6.4
Std. Deviation Roll Gradient, Sigma	1.13	
Maximum Roll Gradient	7.4	11.3
Minimum Roll Gradient	2.7	1.5
Maximum Roll Gradient +25%	9.25	14.13
Minimum Roll Gradient -25%	2.03	1.13
Mean Roll Gradient +3 Sigma	8.18	
Mean Roll Gradient -3 Sigma	1.37	
Avgerage Production Year Range	‘93 - ‘96	‘80 - ‘87

Chart 1-6. Summary of Sideslip Gradient Data

Model Year	Make	Model	Sideslip Gradient Deg./g, 50 Mph
1977	Renault	LeCar	-2.35
1982	Toyota	Starlet	-2.65
1984	Honda	CRX	-2.44
1984	Honda	Civic HB	-2.60
1982	Honda	Civic 4dr	-2.14
1983	Nissan	Sentra	-2.49
1980	Chevrolet	Chevette	-2.54
1983	Volkswagen	Jetta	-2.83
1983	Dodge	Omni	-2.81
1987	Datsun	510	-3.97
1982	B.M.W	320i	-2.72
1987	Hyundai	Excel	-2.26
1983	Toyota	Camry	-3.03
1985	Nissan	Stanza4dr	-2.83
1985	Chevrolet	Cavalier	-2.42
1989	Ford	Escort	-2.86
1980	Datsun	2oosx	-1.61
1984	Pontiac	Fiero	-4.55
1985	Oldsmobile	Ciera	-2.86
1987	Ford	T'bird	-2.04
1980	Buick	LeSabre	-3.22

Maximum Sideslip Gradient	-1.61
Minimum Sideslip Gradient	-4.55
Mean Sideslip Gradient	-2.72
Std. Deviation, Sigma	0.63
Mean Sideslip Gradient +3 Sigma	-0.83
Mean Sideslip Gradient -3 Sigma	4.62
Maximum Sideslip Gradient +25%	-1.21
Minimum Sideslip Gradient -25%	-5.69

Chart 1 - 7 - ***Summary of Steering Torque Gradient Data***

30 Mph - Units for Steerina Torque Gradient - In.-Lbf./g

Mean Steerina Toraue Gradient	156.5
Standard Deviation of Steering Torque Gradient	32.6
Maximum Steering Torque Gradient Data	232.0
Minimum Steering Torque Gradient Data	87.0
Maximum Steering Toraue Gradient Data +25%	290.0
Minimum Steering Torque Gradient Data - 25%	65.3
Mean Steerina Toraue Gradient +3 Sigma	254.5
Mean Steering Torque Gradient -3 Sigma	58.6

45 Mph - Units for Steering Torque Gradient - In.-Lbf./g

Mean Steering Torque Gradient	158.4
Standard Deviation of Steerina Toraue Gradient	30.3
Maximum Steering Torque Gradient Data	243.0
Minimum Steering Torque Gradient Data	96.0
Maximum Steerina Toraue Gradient Data +25%	303.8
Minimum Steering Torque Gradient Data - 25%	72.0
Mean Steering Torque Gradient +3 Sigma	249.3
Mean Steering Toraue Gradient -3 Sigma	67.6

60 Mph - Units for Steering Torque Gradient - In.-Lbf./g

Mean Steering Torque Gradient	164.6
Standard Deviation of Steerina Toraue Gradient	31.8
Maximum Steering Torque Gradient Data	239.0
Minimum Steenna Toraue Gradient Data	99.0
Maximum Steering Torque Gradient Data +25%	298.8
Minimum Steering Torque Gradient Data - 25%	74.3
Mean Steerina Toraue Gradient +3 Sigma	260.1
Mean Steering Torque Gradient -3 Sigma	69.1

75 Mph - Units for Steerina Torque Gradient - In.-Lbf./g

Mean Steering Torque Gradient	161.7
Standard Deviation of Steering Toraue Gradient	31.4
Maximum Steering Torque Gradient Data	223.0
Minimum Steerina Toraue Gradient Data	92.0
Maximum Steering Torque Gradient Data +25%	278.5
Minimum Steerina Toraue Gradient Data - 25%	69.0
Mean Steering Torque Gradient +3 Sigma	256.0
Mean Steering Torque Gradient -3 Sigma	67.4

Chart 1-8. ***Steering Torque Gradient vs. Vehicle Test Weight***

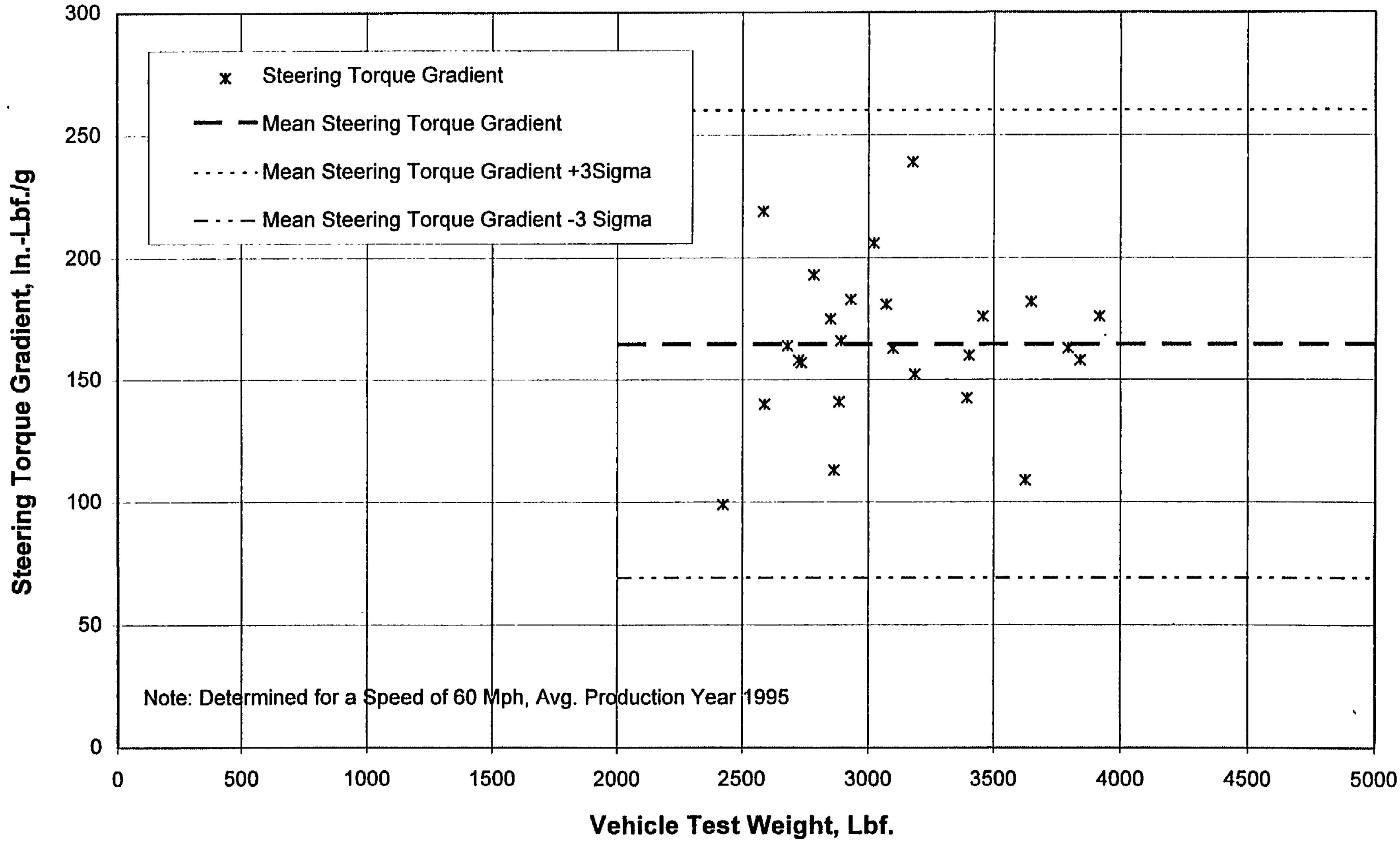

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Chart 1-9. **_Steering Torque Gradient vs. Understeer Gradient_**

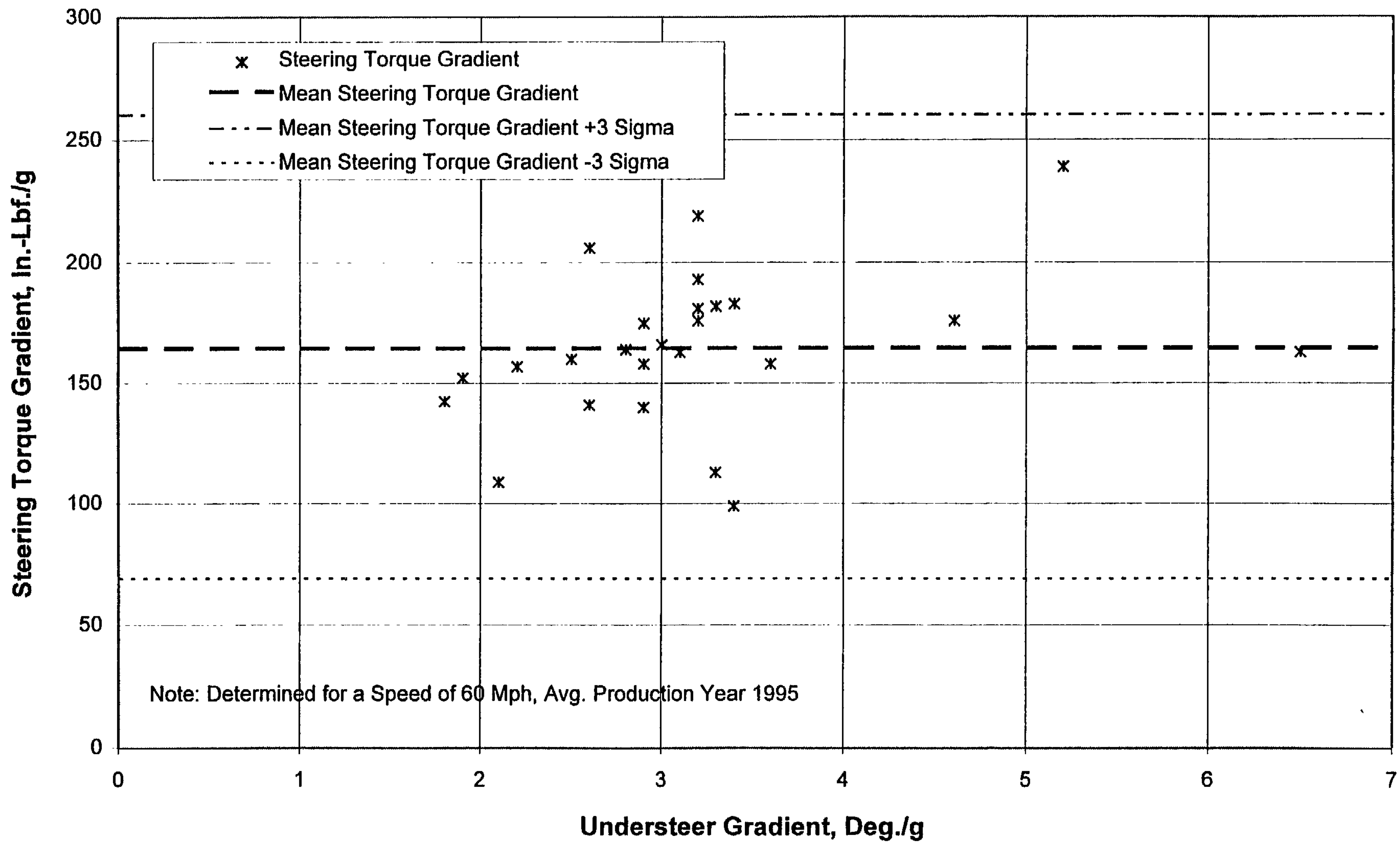

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Chart 1 - 10. ***Summary of Steering Torsional Stiffness***

30 **Mph** - Units for Steering Torsional Stiffness - In.-Lbf./deg.

Mean Steering Torsional Stiffness	0.90
Standard Deviation of Steering Torsional Stiffness	0.20
Maximum Steerina Torsional Stiffness	1.44
Minimum Steering Torsional Stiffness	0.58
Maximum Steering Torsional Stiffness +25%	1.80
Minimum Steering Torsional Stiffness - 25%	0.44
Mean Steering Torsional Stiffness +3 Sigma	1.49
Mean Steering Torsional Stiffness -3 Sigma	0.31

45 Mph - Units for Steering Torsional Stiffness - In.-Lbf./deg.

Mean Steering Torsional Stiffness	1.44
Standard Deviation of Steering Torsional Stiffness	0.28
Maximum Steering Torsional Stiffness	2.05
Minimum Steering Torsional Stiffness	0.97
Maximum Steering Torsional Stiffness +25%	2.56
Minimum Steering Torsional Stiffness - 25%	0.73
Mean Steering Torsional Stiffness +3 Sigma	2.29
Mean Steerina Torsional Stiffness -3 Sigma	0.59

60 Mph - Units for Steerina Torsional Stiffness - In.-Lbf./deg.

Mean Steering Torsional Stiffness	1.86
Standard Deviation of Steering Torsional Stiffness	0.36
Maximum Steering Torsional Stiffness	2.63
Minimum Steerina Torsional Stiffness	1.27
Maximum Steering Torsional Stiffness +25%	3.29
Minimum Steerina Torsional Stiffness - 25%	0.95
Mean Steering Torsional Stiffness +3 Sigma	2.95
Mean Steering Torsional Stiffness -3 Sigma	0.78

75 Mph - Units for Steering Torsional Stiffness - In.-Lbf./deg

Mean Steering Torsional Stiffness	2.10
Standard Deviation of Steering Torsional Stiffness	0.43
Maximum Steering Torsional Stiffness	2.85
Minimum Steering Torsional Stiffness	1.40
Maximum Steering Torsional Stiffness +25%	3.56
Minimum Steering Torsional Stiffness - 25%	1.05
Mean Steering Torsional Stiffness +3 Sigma	3.40
Mean Steering Torsional Stiffness -3 Sigma	0.82

Chart l-11. ***Summary of Maximum Lateral Acceleration Data***

Vehicle Number	Where Was Data Obtained	Year	Make	Model 1	Curb Weight Lbf.	Max. Lateral 25 Mph, g	Max. Lateral 50 Mph g
1	NHTSA	1977	Renault	LeCar	1799	0.70	0.70
2	NHTSA	1982	Toyota	Starlet	1804	0.72	0.73
3	NHTSA	1984	Honda	CRX	1864	0.78	0.79
4	NHTSA	1984	Honda	Civic HB	1984	0.78	0.77
5	NHTSA	1982	Honda	Civic 4dr	2224	0.80	0.80
6	NHTSA	1983	Nissan	Sentra	2353	0.66	0.66
7	NHTSA	1980	Chevrolet	Chevette	2299	0.71	0.73
8	NHTSA	1983	Volkswagen	Jetta	2135	0.74	0.74
9	NHTSA	1983	Dodge	Omni	2169	0.77	0.76
10	NHTSA	1987	Datsun	510	2400	0.77	0.78
11	NHTSA	1982	B.M.W	320i	2415	0.72	0.74
12	NHTSA	1987	Hyundai	Excel	2438	0.73	0.72
13	NHTSA	I983	Toyota	Camry	2446	0.76	0.76
14	NHTSA	1985	Nissan	Stanza 4dr	2505	0.75	0.75
15	NHTSA	1985	Chevrolet	Cavalier	2525	0.71	0.71
. 16	NHTSA	1989	Ford	Escort	2708	0.73	0.73
17	NHTSA	1980	Datsun	2oosx	2626	0.79	0.80
18	NHTSA	1984	Pontiac	Fiero	2601	0.72	0.73
19	NHTSA	1985	Oldsmobile	Ciera	2838	0.76	0.75
20	NHTSA	1987	Ford	T'bird	3430	0.72	0.74
21	NHTSA	1980	Buick	LeSabre	4030	0.74	0.75

	NHTSA Report 25 Mph	NHTSA Report 50 Mph	GM Report
Average Max. Lateral Force	0.741	0.745	0.770
Max. Lateral Force	0.800	0.800	0.910
Min. Lateral Force	0.660	0.660	0.590
Max. Lateral + 25%	1 .000	1 .000	1.138
Min. Lateral - 25%	0.495	0.495	0.443
Std. Deviation, Sigma	0.034	0.034	
Avg. Lateral +3Sigma	0.844	0.845	
Avg. Lateral -3Sigma	0.638	0.644	

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Chart l-12. ***Summary of Steering Sensitivity Data***

45 ***Mph*** - Units For Steering Sensitivity = G/100 Deg SWA	Ford Data	GM Data
Mean Steering Sensitivity	0.900	
Std. Deviation of Steering Sensitivity	0.133	-
Maximum Steering Sensitivity	1.200	
Minimum Steering Sensitivity	0.610	-
Maximum Steering Sensitivity +25%	1.500	-
Minimum Steering Sensitivity -25%	0.458	-
Steering Sensitivity +3 Sigma	1.299	
Steering Sensitivity -3 Sigma	0.501	

60 ***Mph*** - Units For Steering Sensitivity = G/100 Deg SWA	Ford Data	GM Data
Mean Steering Sensitivity	1.155	1.17
Std. Deviation of Steering Sensitivity	0.188	-
Maximum Steering Sensitivity	1.600	2.17
Minimum Steering Sensitivity	0.750	0.59
Maximum Steering Sensitivity +25%	2.000	2.71
Minimum Steering Sensitivity -25%	0.563	0.44
Steering Sensitivity +3 Sigma	1.719	
Steering Sensitivity -3 Sigma	0.591	

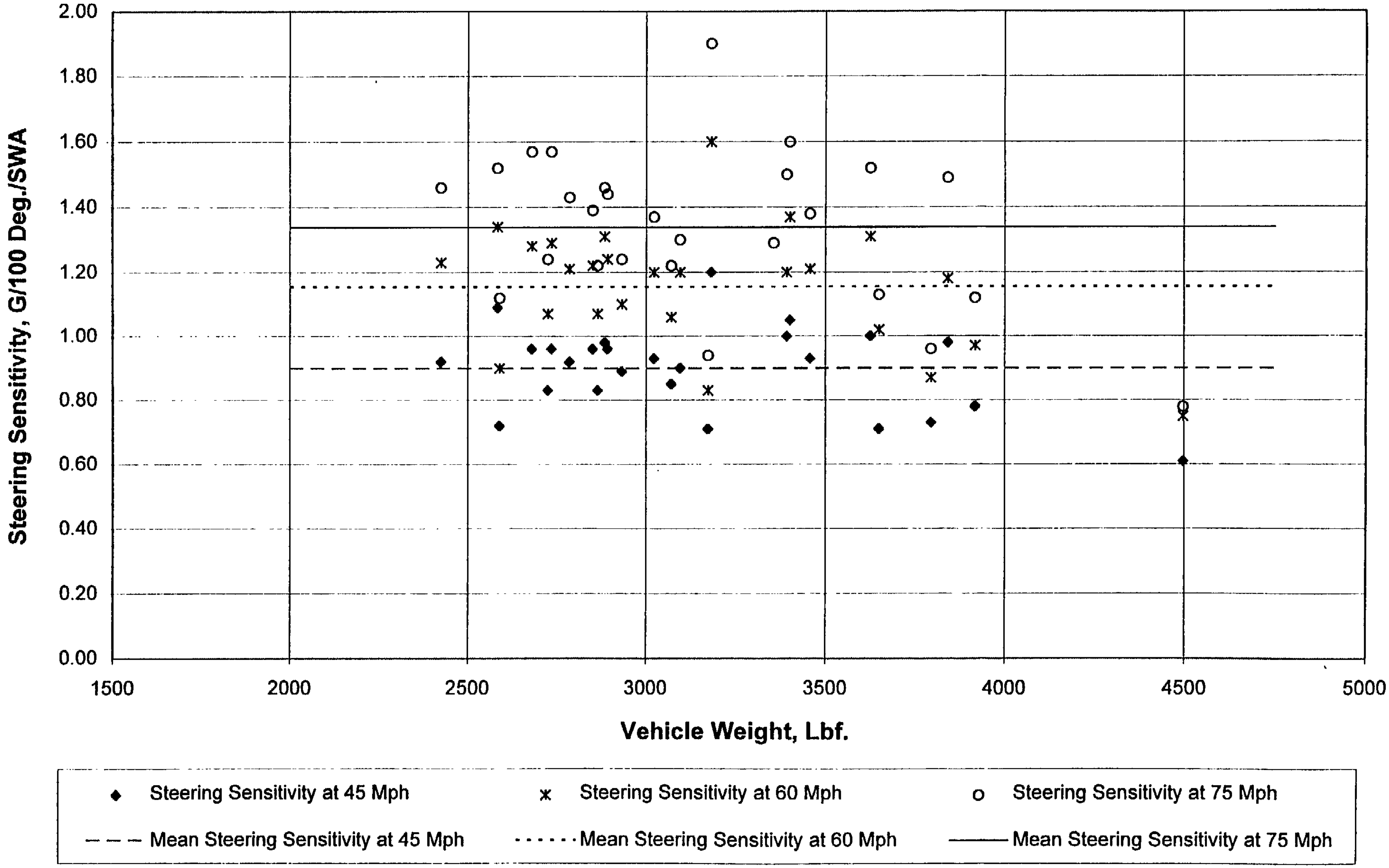
Note: GM Test Results are For A Steed of 62.5 Mph

75 ***Mph*** - Units For Steering Sensitivity = G/100 Deg SWA	Ford Data	GM Data
Mean Steering Sensitivity	1.339	-
Std. Deviation of Steering Sensitivity	0.237	-
Maximum Steering Sensitivity	1.900	-
Minimum Steering Sensitivity	0.780	-
Maximum Steering Sensitivity +25%	2.375	-
Minimum Steering Sensitivity -25%	0.585	-
Steering Sensitivity +3 Sigma	2.051	-
Steering Sensitivity -3 Sigma	0.627	-
Vehicle Production Year Range	‘93 - ‘96	‘80 - ‘87

STEERSEN.XLS

Compiled From Ford Provided Data

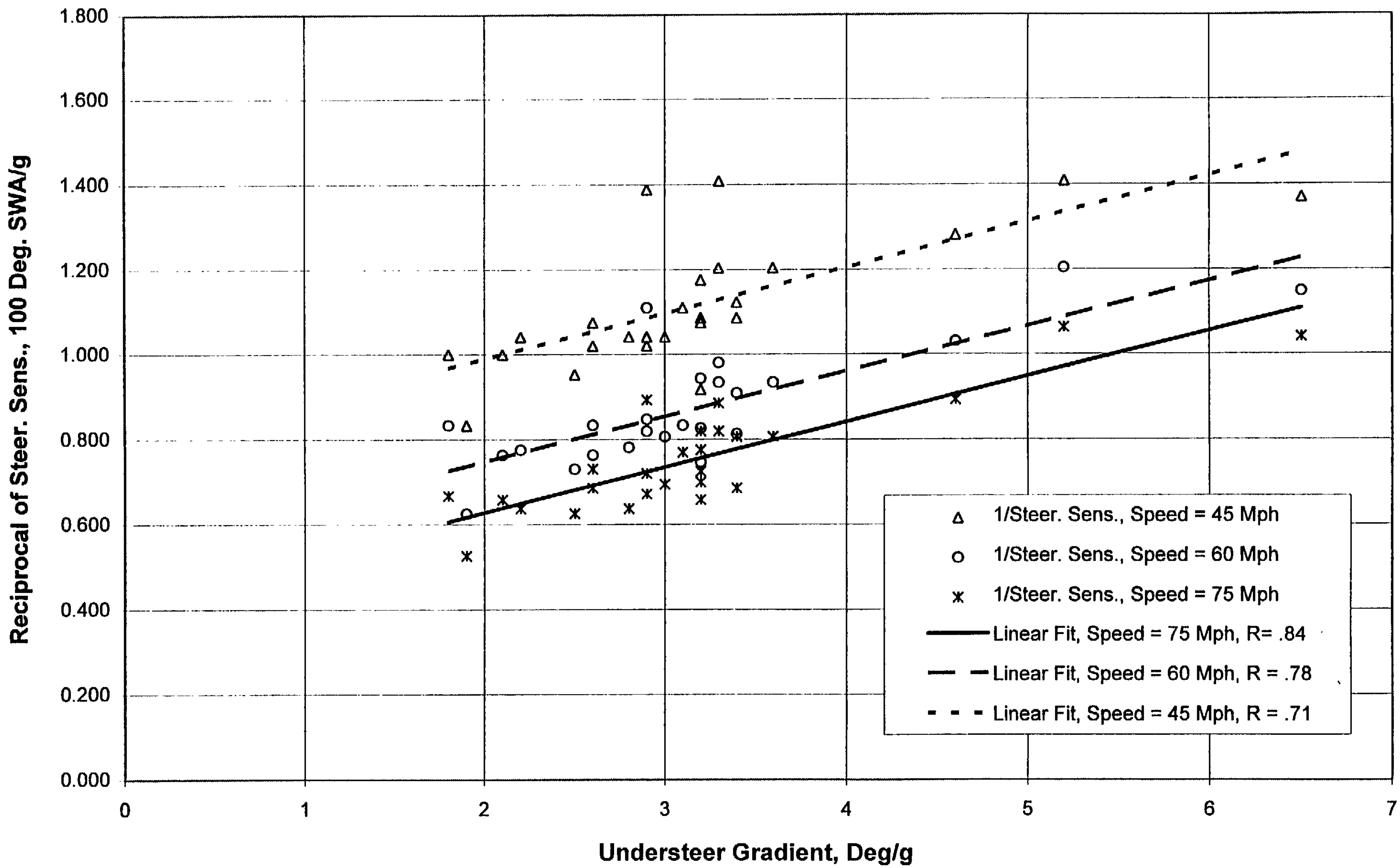
Chart 1-13. **Steering Sensitivity vs. Vehicle Weight**



STEERSEN.XLS

Compiled From Ford Provided Data

Chart 1-14. ***Reciprocal of Steering Sensitivity vs. Understeer Gradient***



STEERSEN.XLS

Chart 1-15. ***Lateral Acceleration -3dB Bandwidth***

45 Mph - Units for Bandwidth - Hz

Mean -3 dB Bandwidth	1.159
Standard Deviation of -3 dB Bandwidth, Sigma	0.168
Maximum -3 dB Bandwidth	1.560
Minimum -3 dB Bandwidth	0.900
Maximum -3 dB Bandwidth +25%	1.950
Minimum -3 dB Bandwidth -25%	0.675
Mean -3 dB Bandwidth +3 Sigma	1.663
Mean -3 dB Bandwidth -3 Sigma	0.655

60 Mph - Units for Bandwidth - Hz

Mean -3 dB Bandwidth	1.140
Standard Deviation of -3 dB Bandwidth, Sigma	0.163
Maximum -3 dB Bandwidth	1.550
Minimum -3 dB Bandwidth	0.880
Maximum -3 dB Bandwidth +25%	1.938
Minimum -3 dB Bandwidth -25%	0.660
Mean -3 dB Bandwidth +3 Sigma	1.628
Mean -3 dB Bandwidth -3 Sigma	0.653

75 Mph - Units for Bandwidth - Hz

Mean -3 dB Bandwidth	1.145
Standard Deviation of -3 dB Bandwidth, Sigma	0.166
Maximum -3 dB Bandwidth	1.550
Minimum -3 dB Bandwidth	0.830
Maximum -3 dB Bandwidth +25%	1.938
Minimum -3 dB Bandwidth -25%	0.623
Mean -3 dB Bandwidth +3 Sigma	***1.643***
Mean -3 dB Bandwidth -3 Sigma	0.646

Compiled From Ford Provided Data

Chart 1-16. **_Lateral Acceleration -3dB Bandwidth vs. Vehicle Test Weight_**

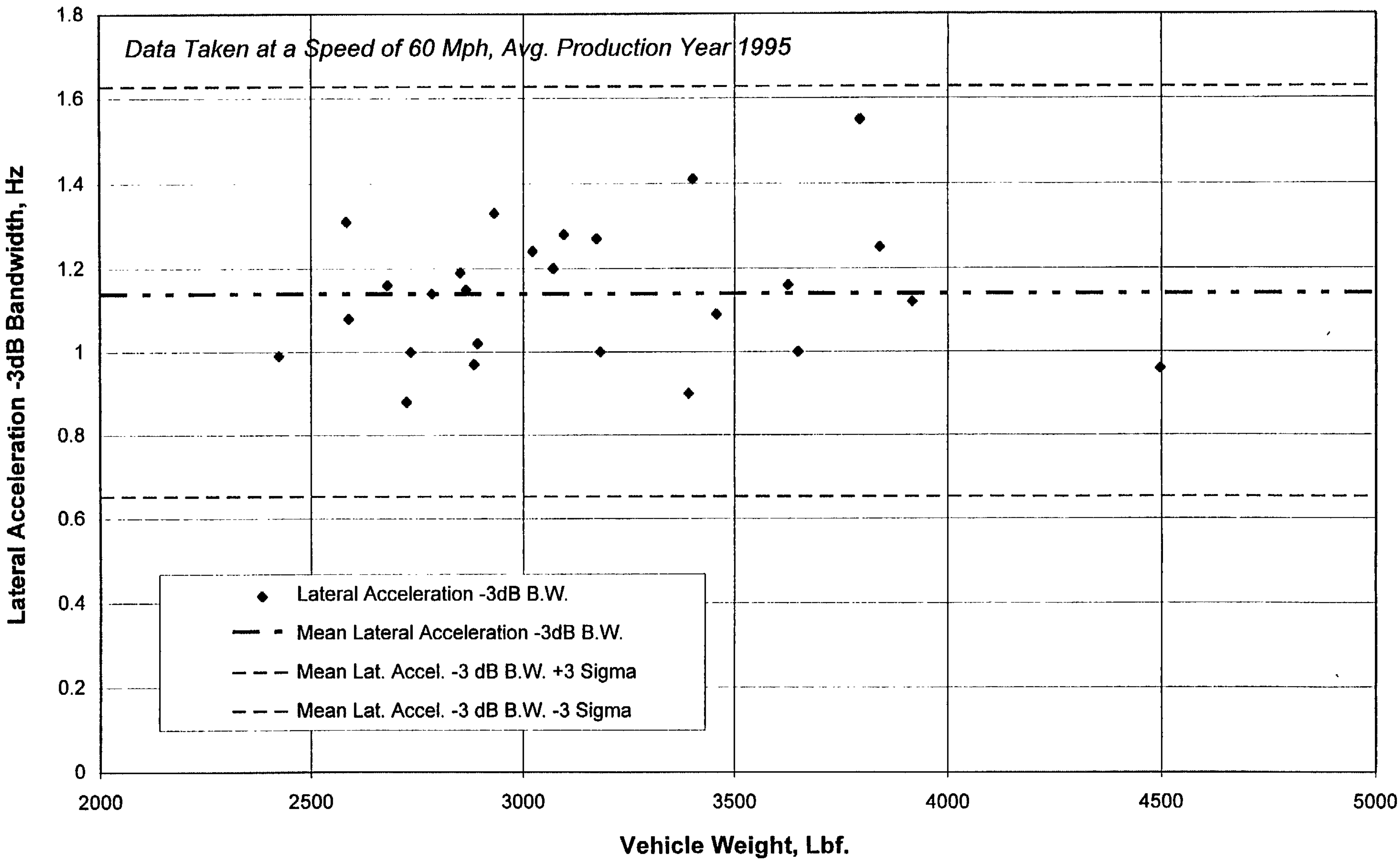


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Chart l-17. ***Summary of Yaw Rate % Overshoot Data***

Model Year	Make	Model	Yaw Rate %Overshoot Ay=.4g, 50 Mph
1977	Renault	LeCar	14.289
1982	Toyota	Starlet	9.103
1984	Honda	CRX	12.407
1984	Honda	Civic HB	11.252
1982	Honda	Civic 4dr	13.709
1983	Nissan	Sentra	25.418
1980	Chevrolet	Chevette	20.109
1983	Volkswagen	Jetta	9.926
1983	Dodge	Omni	10.472
1987	Datsun	510	8.397
1982	B.M.W	320i	8.327
1987	Hyundai	Excel	9.74
1983	Toyota	Camry	9.548
1985	Nissan	Stanza4dr	11.989
1985	Chevrolet	Cavalier	14.84
1989	Ford	Escort	17.953
1980	Datsun	200sx	10.239
1984	Pontiac	Fiero	4.236
1985	Oldsmobile	Ciera	9.566
1987	Ford	T'bird	9.723
1980	Buick	LeSabre	15.847

Mean Yaw Rate % Overshoot	12.2
Maximum Yaw Rate % Overshoot	25.4
Minimum Yaw Rate % Overshoot	4.2
Standard Deviation of Yaw Rate % Overshoot	4.7
Mean Yaw Rate % Overshoot +3 Sigma	26.3
Mean Yaw Rate % Overshoot -3 Sigma	0.0
Maximum Yaw Rate % Overshoot +25%	31.8
Minimum Yaw Rate % Overshoot -25%	3.2

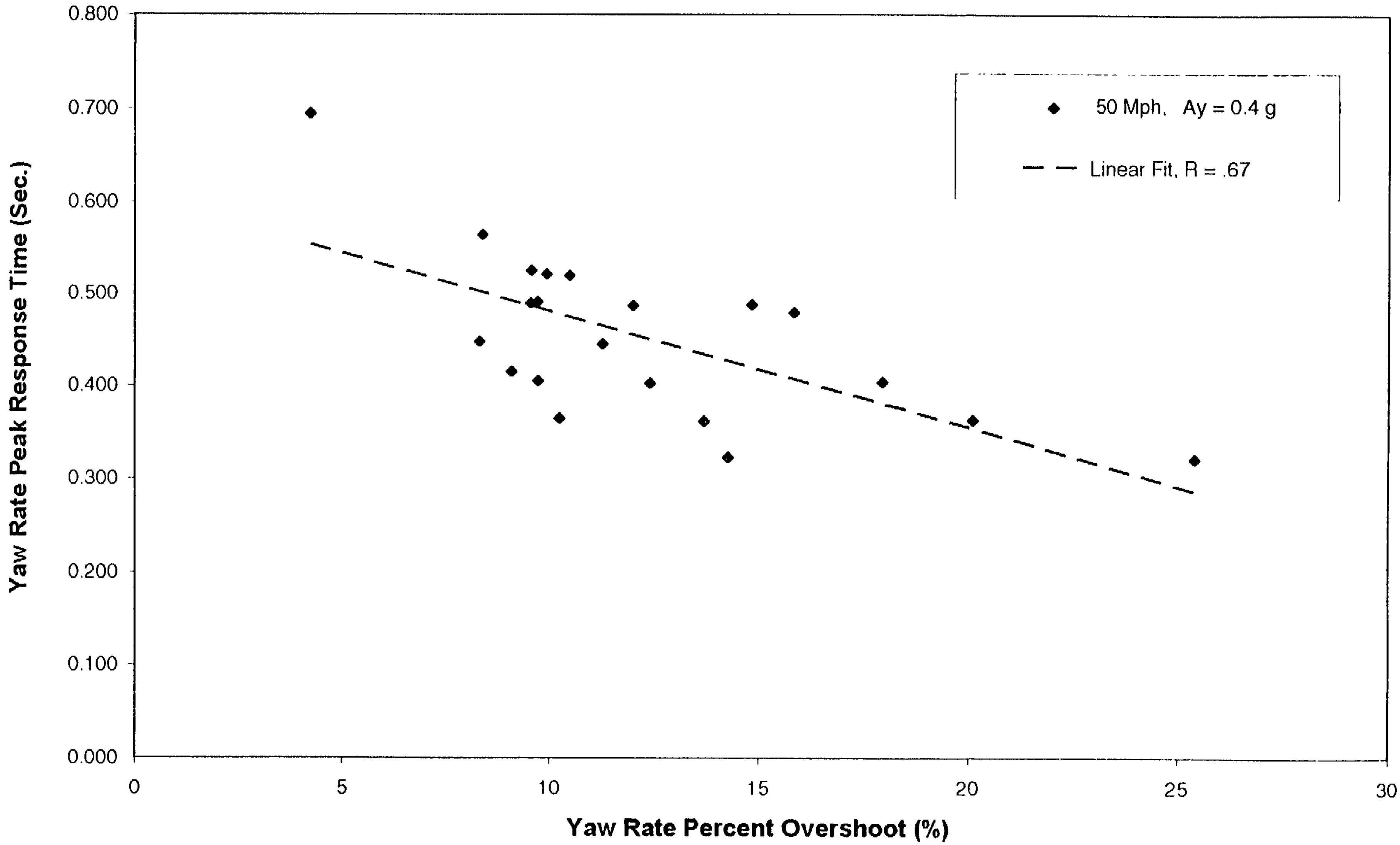
Chart l-18. ***Summary of Time to Peak Yaw Response***

Model Year	Make	Model	Time To Peak Yaw Rate Response Ay = .4g, 50 Mph, Sec.
1977	Renault	LeCar	0.322
1982	Toyota	**Starlet**	0.415
1984	Honda	CRX	0.402
1984	Honda	Civic HB	0.445
1982	Honda	Civic 4dr	0.361
1983	Nissan	Sentra	0.320
1980	Chevrolet	Chevette	0.362
1983	Volkswagen	Jetta	0.521
1983	Dodge	Omni	0.520
1987	Datsun	510	0.564
1982	B.M.W	320i	0.447
1987	Hyundai	Excel	0.405
1983	Toyota	Camry	0.489
1985	Nissan	Stanza4dr	0.487
1985	Chevrolet	Cavalier	0.488
1989	Ford	Escort	0.403
1980	Datsun	2oosx	0.364
1984	Pontiac	Fiero	0.694
1985	Oldsmobile	Ciera	0.525
1987	Ford	T'bird	0.491
1980	Buick	LeSabre	0.479

Time to Peak Yaw Rate Response. Seconds

Maximum Time to Peak Yaw Rate Resoonse	0.694
Minimum Time to Peak Yaw Rate Response	0.320
Mean Time to Peak Yaw Rate Response	0.453
Std. Deviation	0.089
Mean Time to Peak Yaw Rate Response +3 Sigma	0.720
Mean Time to Peak Yaw Rate Response -3 Sigma	0.185
Maximum Time to Peak Yaw Rate Response +25%	0.868
Minimum Time to Peak Yaw Rate Response -25%	0.240

Chart 1-19. ***Yaw Rate Peak Response Time vs. Yaw Rate Percent Overshoot***



METRIC_3.XLS

2.0 AN ANALYSIS OF THE VDTV, ITS ABILITY TO EMULATE A RANGE OF VEHICLES, AND A SUMMARY

2. 1 Introduction

Chart 2-1, Steer Subsystem Feedback's, is a summary of the subsystem feed used in the analysis. Each of the following sections describes one chart, which is numbered and titled to match the section.

2.2 Weight and Inertia Calcuiations for the VDTV

Chart 2-2 contains estimates of weights and locations that were derived to provide estimated changes in the vehicle sprung and unsprung masses, the corresponding center of gravity locations, and inertias. RHO refers to the radius of gyration about the item's own center of gravity. IZ is the yaw moment of inertia of the entire vehicle about cg, while IXS is the moment of inertia in roll of the sprung mass about the roll axis (450.8 ft-lb-sec2).

2.3 Summary of Estimated VDTV Vehicle Data

This chart presents most of the vehicle parameters needed by MRA's computer program to perform calculations. Data were primarily obtained from Ford, through MDI. Note that MRA assumed that the compliances are unchanged. This means that the harshness shouldn't be much different for the VDTV than for the Taurus SHO. However, to reduce the friction about the steer axis, it may be necessary to eliminate or modify the amount of isolation by elastomers in the steering system

Both the self-aligning torque and lateral force steer compliances are understeer effects, giving an understeer gradient of the baseline Taurus of about 3 deg/g.

2.4 Front and Rear Steering Subsystems Analysis Results

These are conclusions from MRA's memo dated October 30,1996, and attached as Appendix A. Bandwidth numbers have been reduced to agree with the definition given by Allan Lee in one of his papers; that is, dB = 20 log10 (amplitude ratio), so that -3 dB corresponds to .707 amplitude ratio. MRA used dB = 10 log10 (amplitude ratio), so that -3 dB corresponds to 0.5 amplitude ratio. (Electrical engineers use 20 for power and 10 for amplitude.) Conclusions are still valid because it was found that 15 to 20 Hz of bandwidth is adequate for even the most stressing of simulation cases. That is, emulation of an understeer gradient of 10, for speeds of 75 or 40 mph doesn't show any significant difference between 15 and 30 Hz of natural frequency (equal to the bandwidth for a damping factor of 0.707).

Chart 2-1.

STEER SUBSYSTEM FEEDBACKS

Feedback Variable		Used to Vary
Front Steer	Rear Steer	
Sideslip Angle	Sideslip Angle	Understeer (75 mph) Acceleration Rise Time (80 km/hr)
Sideslip Rate Yaw Accel.	Sideslip Rate Yaw Accel. t	Percent Overshoot in Yaw Response Time to Peak Yaw Rate Response Acceleration Rise Time (80 km/hr)
Yaw Rate	-----	Understeer (40 mph)
Lateral Accel.	Lateral Accel.	Understeer (40 mph) Understeer (75 mph)
Roll Angle	Roll Angle	Roll Decoupling from Yaw/Sideslip
Roll Accel.	Roll Accel.	Roll Decoupling from Yaw/Sideslip
Steering Wheel Ang.		All Cases
	Steering Wheel Ang.	Steady State Sideslip Response (Trial Cases, not to Satisfy Goals)
	Front Wheel Angle	Sideslip, Yaw Rate Response (Trial Cases, not to Satisfy Goals)

Chart 2-2. Weight and Inertia Calculations for VDTV **DVDTV6.XLS**

ITEM	WEIGHT W LB	HEIGHT Z IN	DISTANCE X IN	RADIUS OF GYRATION RHO XXS ABOUT OWN CG IN	RHO ZZ IN	INERTIAS IZ INCLUDING XFER FT-LB-SEC^2	IXS
VDTV-ESTIMATED							
FRONT UNSPRUNG	240	13	0	30.44	29.52	129.4	52.3
REAR UNSPRUNG	200	13	106.32	31.2	29.52	225.5	45.6
TAURUS SPRUNG	3122	22.29	38.4	23.41	49.33	1693.1	369.2
1. EXTRA BATTERY	40	26	0	3	3	14.1	0.2
2. ANTI-ROLL BAR HYDRAULICS	0			5	3	0.0	0.0
3. FRONT ELECTRIC STEERING	50	11	8	5	3	11.4	1.6
4. REAR ELECTRIC STEERING	50	11	98	5	3	36.0	1.6
5. FRONT ACTIVE ANTI-ROLL BAR	40	11	8	5	3	9.1	1.3
6. FRONT ACTIVE ANTI-ROLL BAR	40	11	98	5	3	28.8	1.3
7. COMPUTERS (REAR SEAT)	40	24	66	3	3	5.8	0.1
8. LAPTOP (FRONT DASH)	10	30	30	2	2	0.2	0.1
9. ROLL CAGE	100	36	50	40	30	21.4	38.6
10.INSTRUMENTATON	40	22	40	50	20	3.5	21.6
11.MISCELLANEOUS	28	22	40	50	20	2.4	15.1
SPRUNG	3560	22.18	38.40			1825.7	450.8
TOTAL	4000	21.17	40.34	25.22	50.27	2180.6	548.8

Chart 2-3. Summary of Estimated VDTV Vehicle Data DVDTV6.XLS

HEIGHT TO TOTAL CG	21.17	IN	1.7643	FT
FRONT ROLL CENTER HEIGHT	1.82	IN	0.1517	FT
REAR ROLL CENTER HEIGHT	0.26	IN	0.0217	FT
ROLL AXIS HEIGHT AT CGS	0.83	IN	0.0688	FT
HT. SPRUNG CG TO ROLL AXIS	21.36	IN	1.7797	FT
IX-SPRUNG MASS (OWN CG)	548.8	FT-LB-SEC^2		
XFER TERM TO ROLL AXIS	350.3	FT-LB-SEC^2		
TOTAL IXS ABOUT ROLL AXIS	899	FT-LB-SEC^2		
TOTAL IZ ABOUT TOTAL CG	2199	FT-LB-SEC^2		
FRONT AXLE TO CG = a	40.34	IN	3.3614	FT
REAR AXLE TO CG = b	65.64	IN	5.4702	FT
TRACK WIDTH	61.2	IN	5.1000	FT
FRONT:				
UNSPRUNG WEIGHT	240	LB		
CG HEIGHT	13	IN	1.083	FT
TOE ANGLE, DEG	-0.02	DEG		
CASTER TRAIL	1.03	IN	0.086	FT
ROLL CAMBER	0.741			
ROLL STEER	0.0071			
LAT. FORCE COMPL. STEER (MUF)	-0.000531	DEG/LB	-9.267E-06	RAD/LB
LAT. FORCE COMPL. CAMBER (DGDSF)	-0.000668	DEG/LB	-1.166E-05	RAD/LB
SAT COMPL. STEER (ETAF)	0.000302	DEG/IN-LB	6.325E-05	RAD/FT-LB
SAT COMPL. CAMBER (DGDAF)	0.000014	DEG/IN-LB	2.932E-06	RAD/FT-LB
ROLL RATE (TOTAL)	10490	IN-LB/DEG	50089.75	FT-LB/RAD
REAR:				
UNSPRUNG WEIGHT	200	LB		
CG HEIGHT	13	IN	1.083	FT
TOE ANGLE, DEG	0.016	DEG		
CASTER TRAIL	NA			
ROLL CAMBER	0.894			
ROLL STEER				
LAT. FORCE COMPL. STEER (MUR)	0.000051	DEG/LB	8.901E-07	RAD/LB
LAT. FORCE COMPL. CAMBER (DGDSR)	-0.000156	DEG/LB	-2.723E-06	RAD/LB
SAT COMPL. STEER (ETAR)	0.00012	DEG/IN-LB	2.513E-05	RAD/FT-LB
SAT COMPL. CAMBER (DGDAR)	0.000006	DEG/IN-LB	1.257E-06	RAD/FT-LB
ROLL RATE (TOTAL)	7063	IN-LB/DEG	33725.825	FT-LB/RAD

Chart 2-4.

Front and Rear Steering Subsystems Analysis Results

Recommendations

- Reduce friction to a minimum
- Add viscous damper on steer angle
- Make provision for reducing compliances, especially on front
- Add' steer angle feedback to obtain precise control of steer angle
- Update analysis as more data become available

Conclusions (based on following the above recommendations)

- Well damped steer angle response is practical
- Precise control of steer angle is achievable
- Bandwidths between 15 and 25 Hz can be obtained, depending upon compliances

2.5 Front Steer Frequency Response, Stiffness: 7600 lbf/in

Chart 2-5 uses the stiffness calculated from the specified SAT steer compliance at the front of the Taurus SHO (1993 model data from Ford). The curve is described in MRA's memo on the steer subsystem, which is dated October 30,1996, and contained in Appendix A. Note that the friction is zero and a steer angle damper is added as indicated. Also note the improvement achievable with steer angle position feedback.

2.6 Rear Steer Frequency Response: Stiffness: 19,000 lbf/in

The stiffness used in Chart 2-6 is calculated from the specified SAT steer compliance for the rear suspension of the Taurus SHO.

2.7 Effect of Roll Decoupling With Increasing Roll Stiffness, Roll Angle Response, 75 MPH

In this chart, roll angle and roll acceleration are introduced into the front and rear steer angles to make the yaw and sideslip (and, therefore, lateral acceleration of the unsprung masses) responses independent of the roll degree of freedom. This has a major advantage in that the decoupled system is only of second order and can be analyzed in a straightforward manner, thus facilitating determination of appropriate gains and variable to use as feedback.

Following charts demonstrate that we can, indeed, make major changes in the roll response while leaving the yaw, sideslip, and lateral acceleration responses substantially unchanged. This chart shows that we have increased the roll stiffness by factors of 4 and 9, thereby increasing the roll frequency by factors of 2 and 3. The corresponding roll gradients are reduced by factors of 4 and 9.

2.8 Effect of Roll Decoupling With Increasing Roll Stiffness, Lateral Acceleration Response, 75 MPH

This chart shows that the lateral acceleration becomes only slightly more stable and has a little overshoot, but the response hardly changes despite the 9 to 1 change in roll stiffness. Without roll decoupling, this response would change much more.

2.9 Effect of Roll Decoupling With increasing Roll Stiffness, Yaw Rate Response, 75 MPH

This chart shows that the yaw response rate becomes only slightly more stable, and has a little less overshoot, but the response hardly changes despite the 9 to 1 change in roll stiffness. Without roll decoupling this response would change much more.

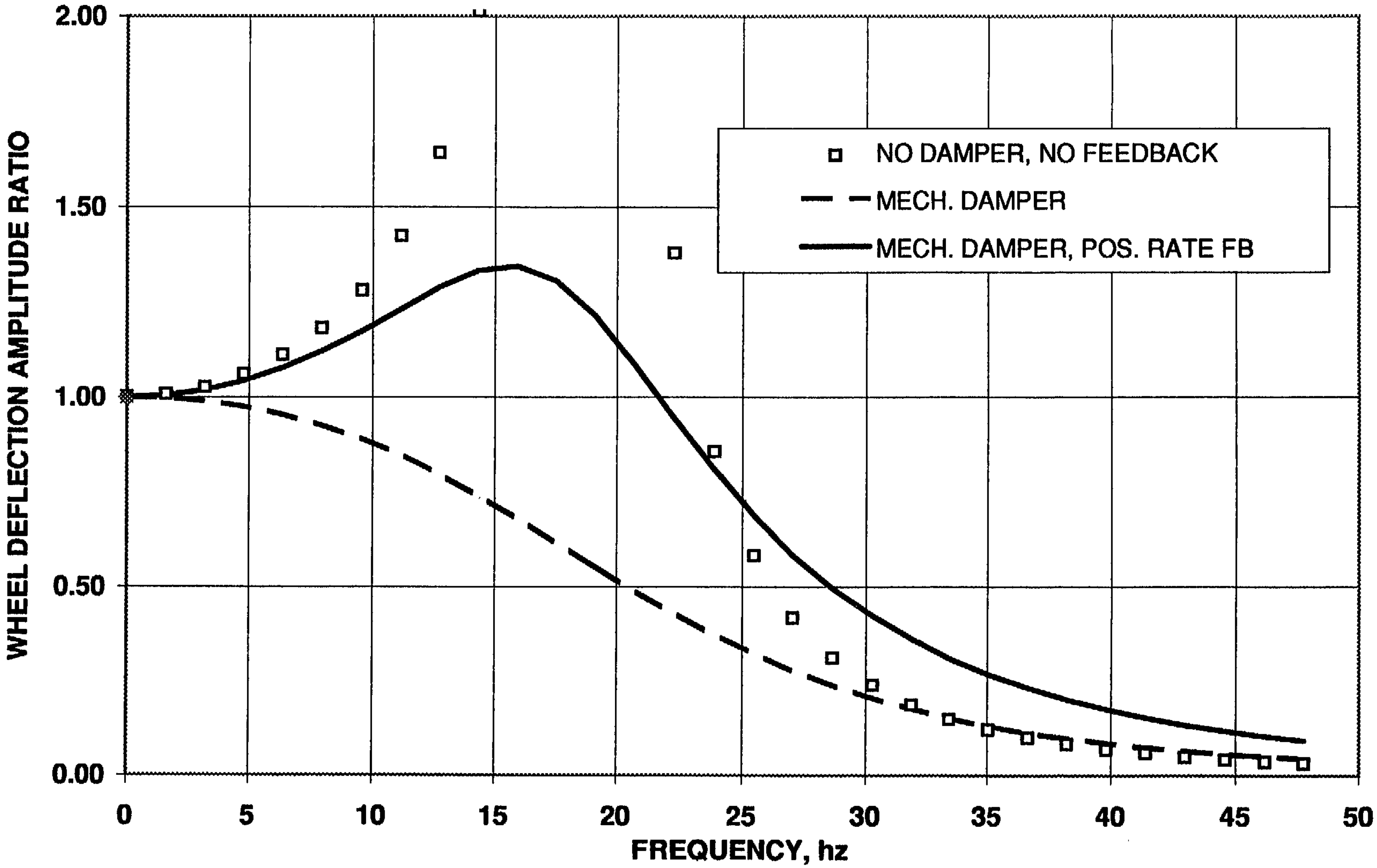


Chart 2-5. **FRONT STEER FREQUENCY RESPONSE**

STIFFNESS: 7600 LB/IN

VDC13.XLS

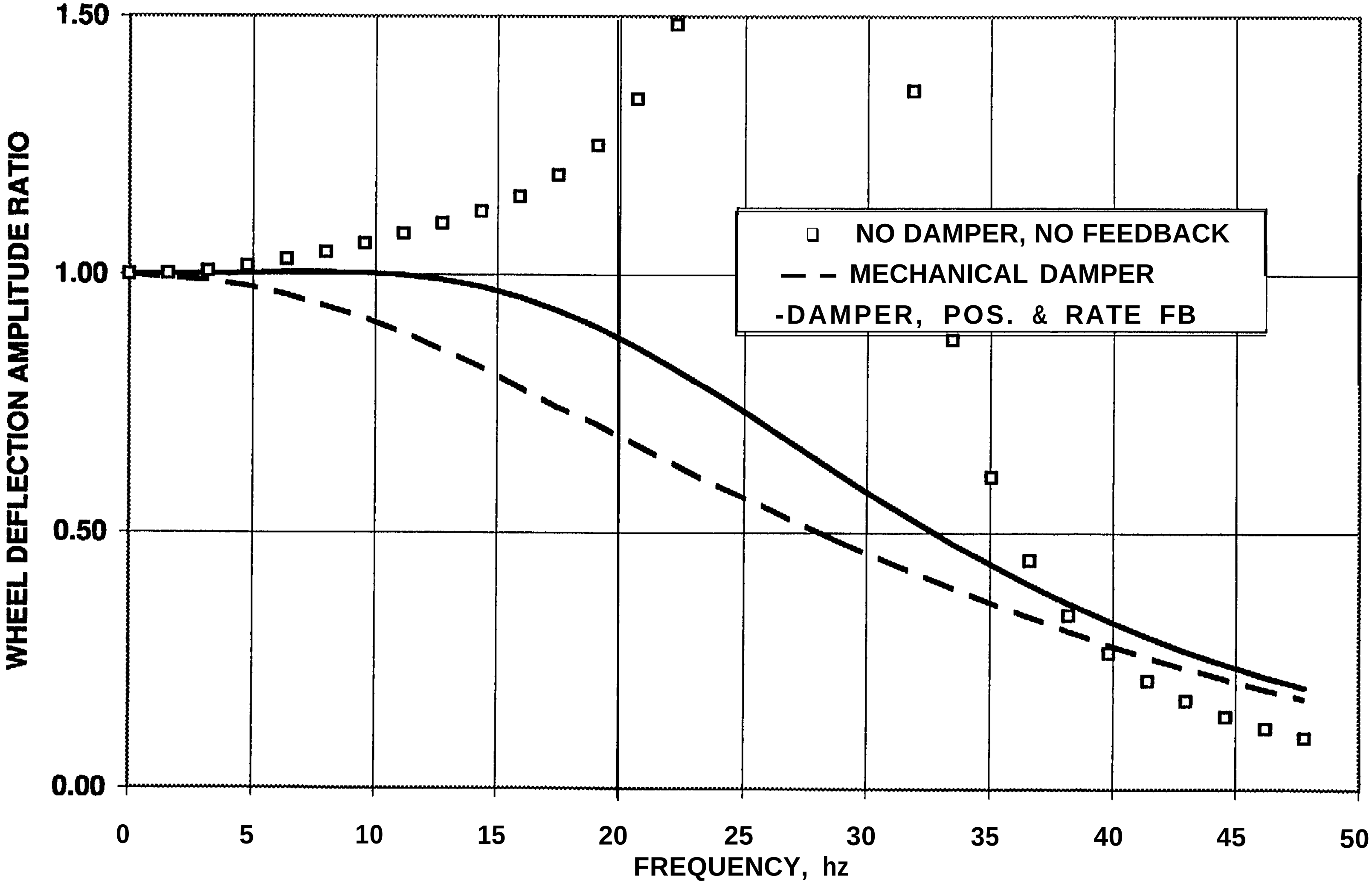


Chart 2-6. **REAR STEER FREQUENCY RESPONSE**

STIFFNESS: 19,000 LB/IN

VDC46.XLS

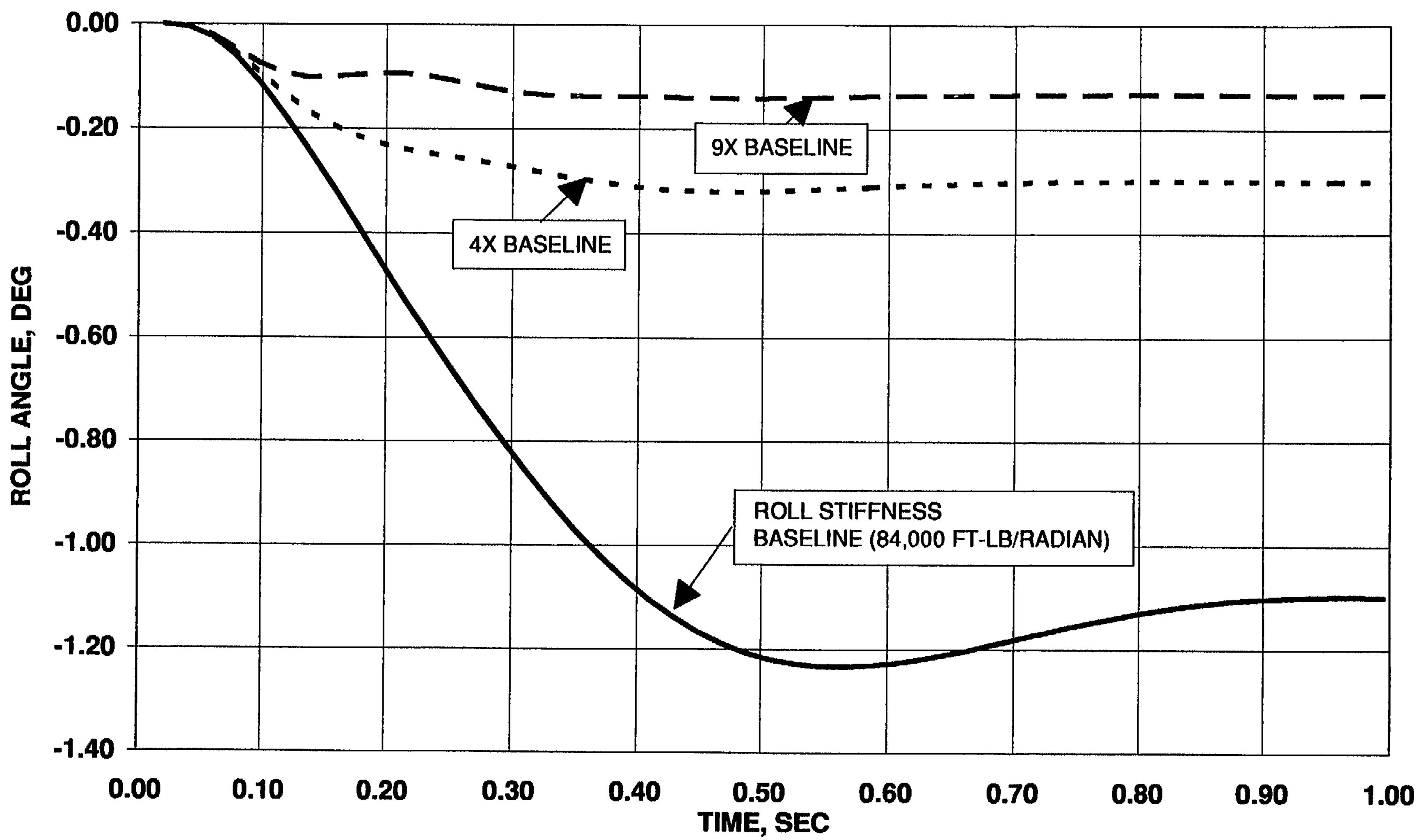


Chart 2-7. **EFFECT OF ROLL DECOUPLING WITH INCREASING ROLL STIFFNESS**
ROLL ANGLE RESPONSE, 75 MPH

V15.XLS

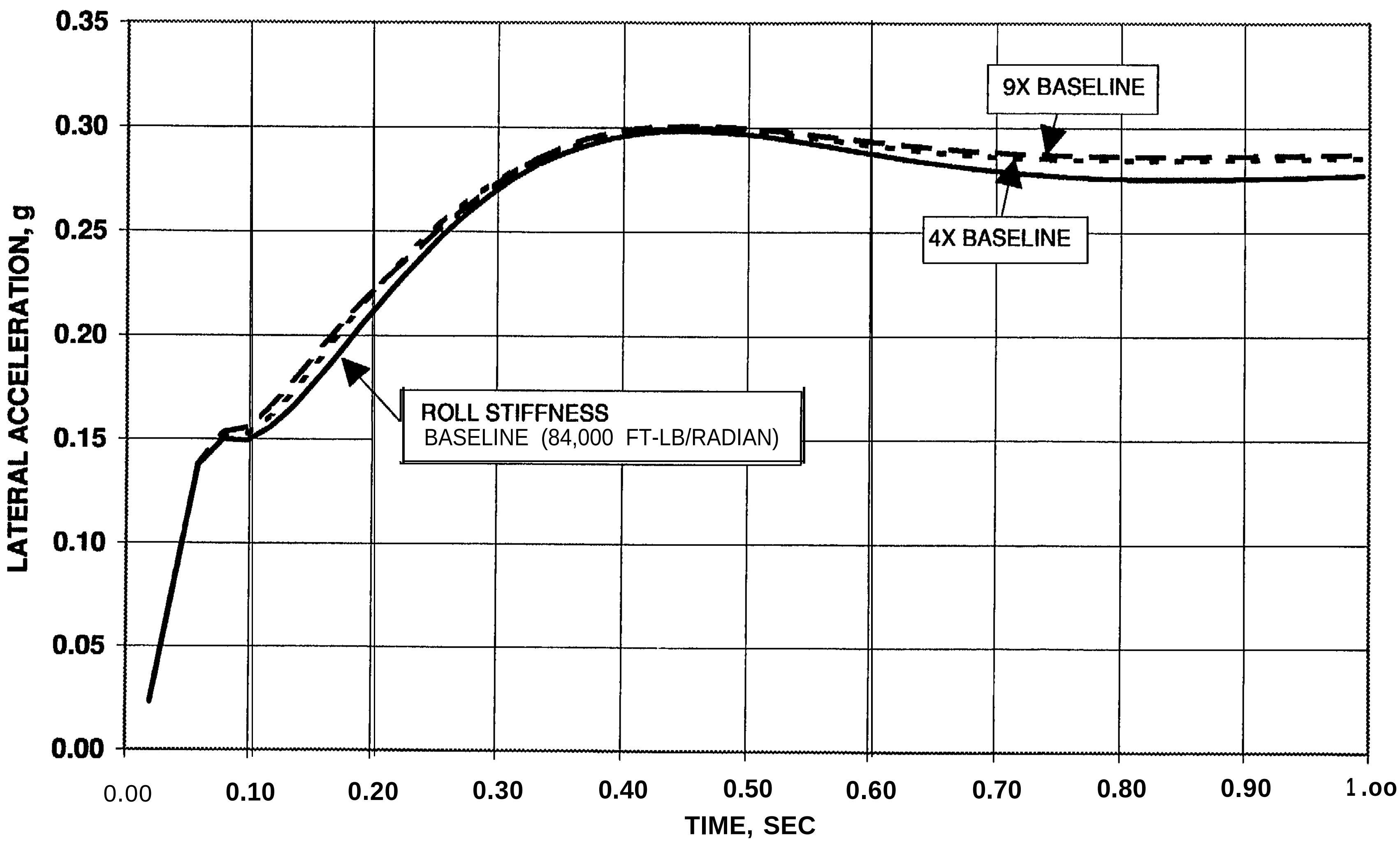


Chart 2-8. **EFFECT OF ROLL DECOUPLING WITH INCREASING ROLL STIFFNESS**
LATERAL ACCELERATION RESPONSE, 75 MPH

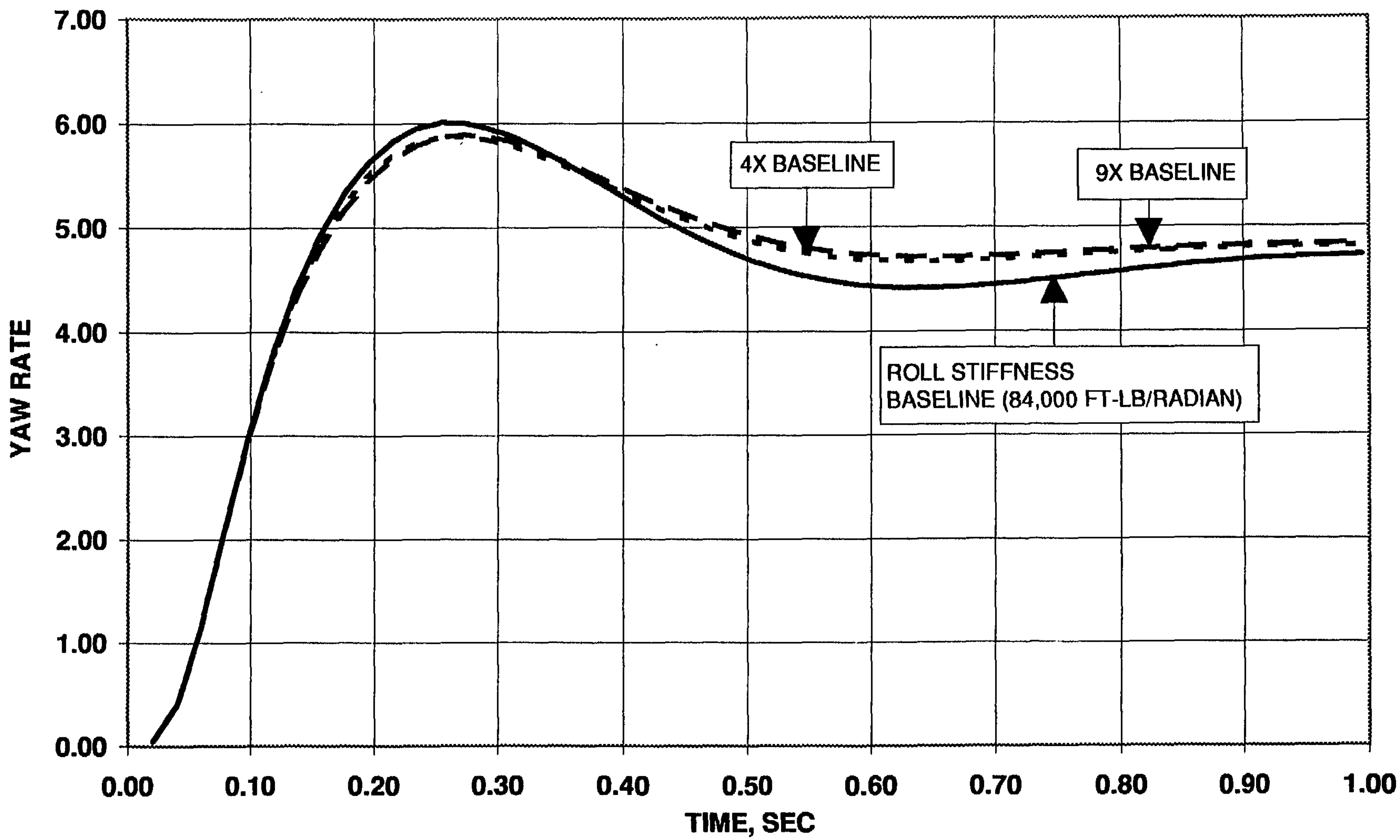


Chart 2-9. **EFFECT OF ROLL DECOUPLING WITH INCREASING ROLL STIFFNESS**
YAW RATE RESPONSE, 75 MPH

V15.XLS

2.10 Effect of Roll Decoupling with increasing Roll Stiffness, Sideslip Angie Response, 75 MPH

Chart 2-10 indicates that, again, sideslip response doesn't change much with the 9 to 1 change in roll stiffness.

2.11 Effect of Roll Decoupling With Variable Roll Damping, Roll Angle, 75 MPH

In this chart, the roll damping has been increased and decreased by factors of about ***2.*** The roll angle response is more oscillatory for the lesser roll damping.

2.12 Effect of Roll Decoupling With Variable Roll Damping, Lateral Acceleration, 75 MPH

Chart 2-12 demonstrates that changing the roll damping has little effect on the resulting yaw-sideslip-lateral acceleration responses.

2.13 Effect of Roll Decoupling With Variable Roll Damping, Sideslip Angle, 75 MPH

Chart 2-13 demonstrates that changing the roll damping has little effect on the resulting yaw-sideslip-lateral acceleration responses.

2.14 Effect of Roll Decoupling With Increasing Roll Stiffness, Roll Angle, 45 MPH

This chart shows about the same result as shown by Chart 2-l 1, but for the lower speed.

2.75 Effect of Roll Decoupling With increasing Roll Stiffness, Yaw Rate, 45 MPH

This chart shows about the same result as shown by Chart 2-12, but for the lower speed.

2.16 Effect of Roll Decoupling With Increasing Roll Stiffness, Lateral Acceleration, 45 MPH

This chart shows about the same result as shown by Chart 2-13, but for the lower speed.

2.17 Effect of Roll Decoupling

Chart 2-17 summarizes roll, yaw, sideslip, and lateral acceleration metrics as affected by roll damping and roll stiffness when roll is decoupled from the other responses.

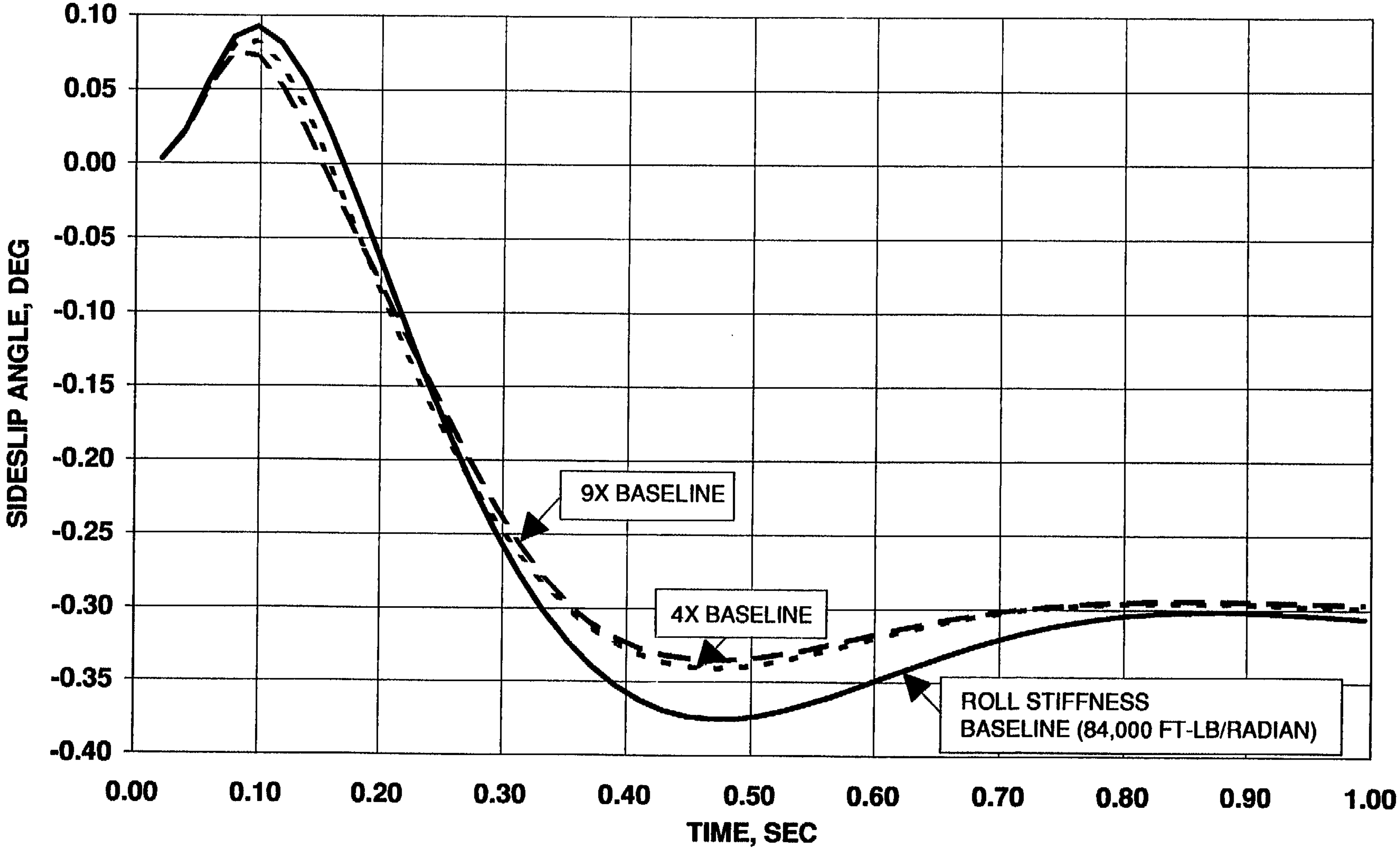


Chart 2-10. **EFFECT OF ROLL DECOUPLING WITH INCREASING ROLL STIFFNESS**
SIDESLIP ANGLE RESPONSE, 75 MPH

V15.XLS

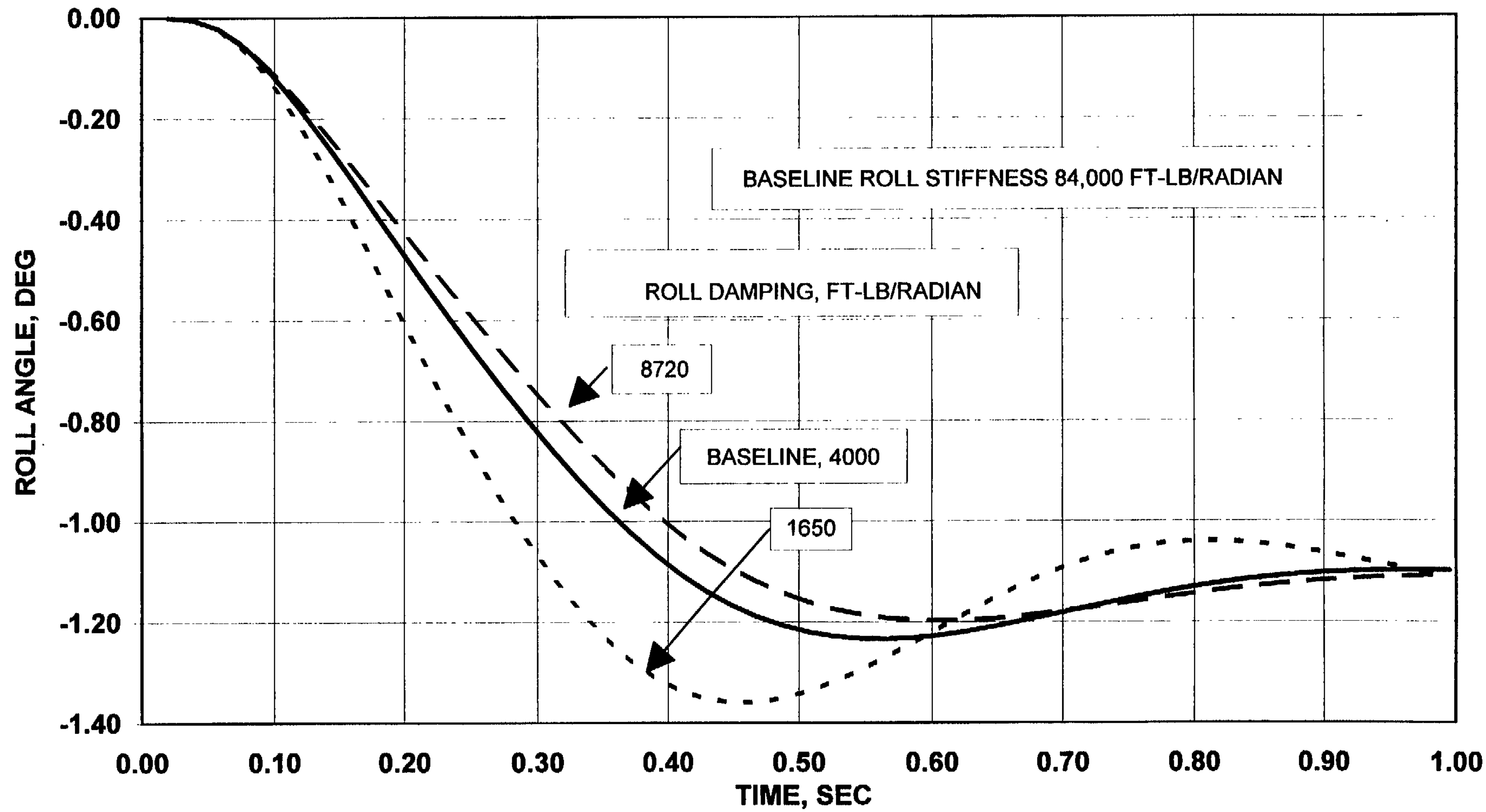


Chart 2-11. **EFF. OF ROLL DECOUPLING WITH VARIABLE ROLL DAMPING**

ROLL ANGLE, 75 MPH

V15.XLS

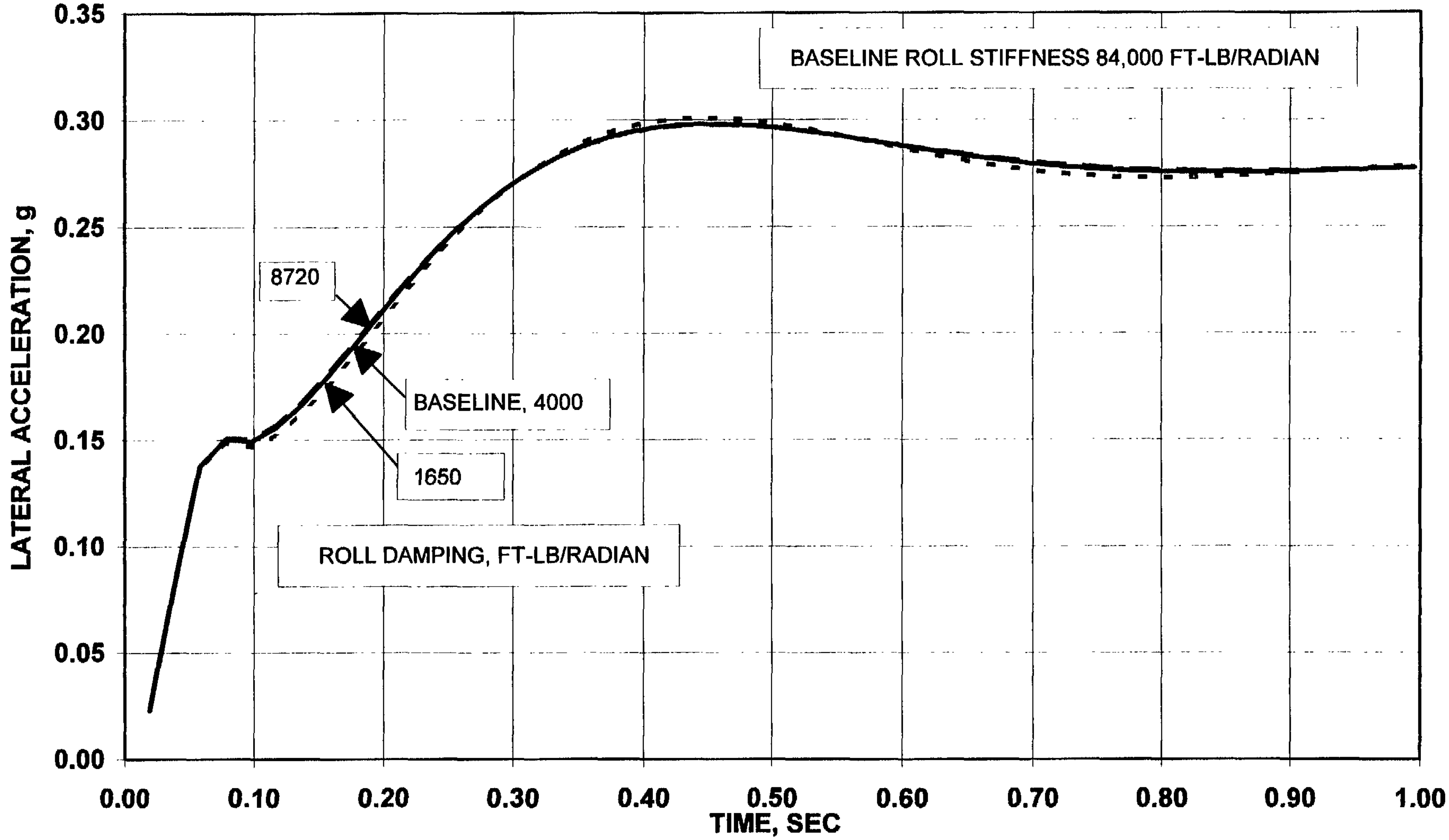


Chart 2-12. **EFF. OF ROLL DECOUPLING WITH VARIABLE ROLL DAMPING**

LATERAL ACCELERATION, 75 MPH

V15.XLS

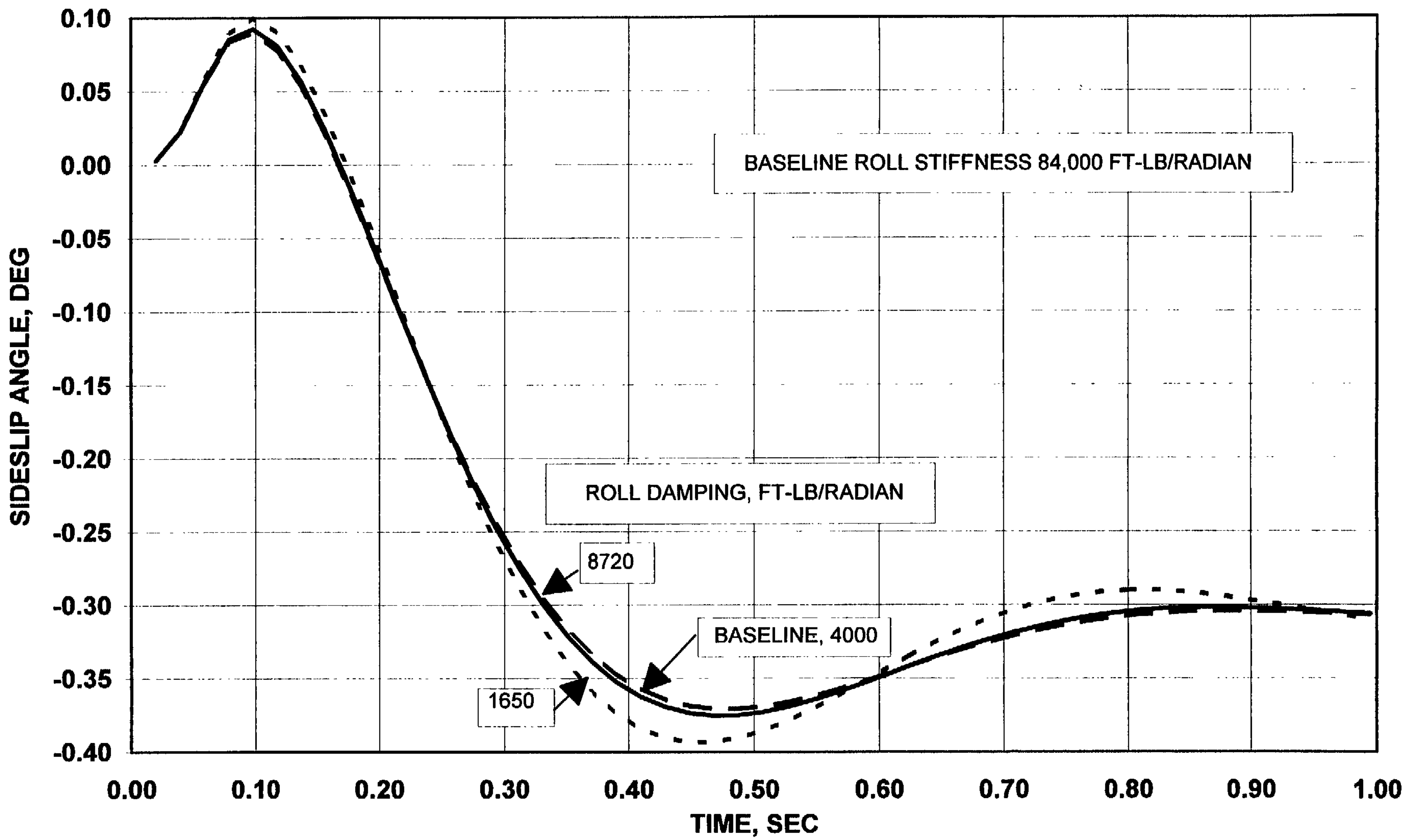


Chart 2-13. **EFFECT OF ROLL DECOUPLING WITH VARIABLE ROLL DAMPING**

SIDESLIP ANGLE, 75 MPH

V15.XLS

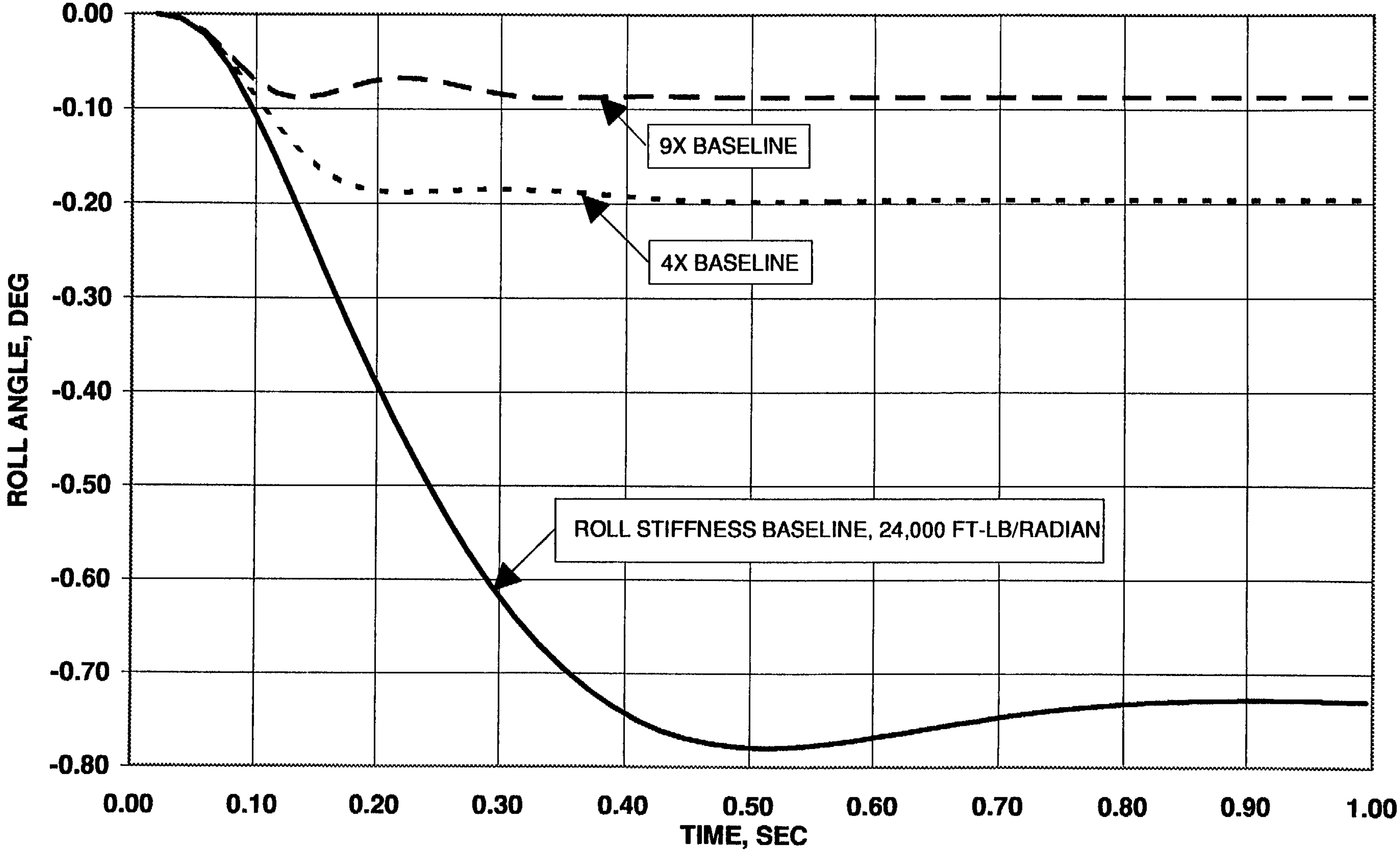


Chart 2-14. **EFF. OF ROLL DECOUPLING W/INCREASING ROLL STIFFNESS**

ROLL ANGLE, 45 MPH

V610.XLS

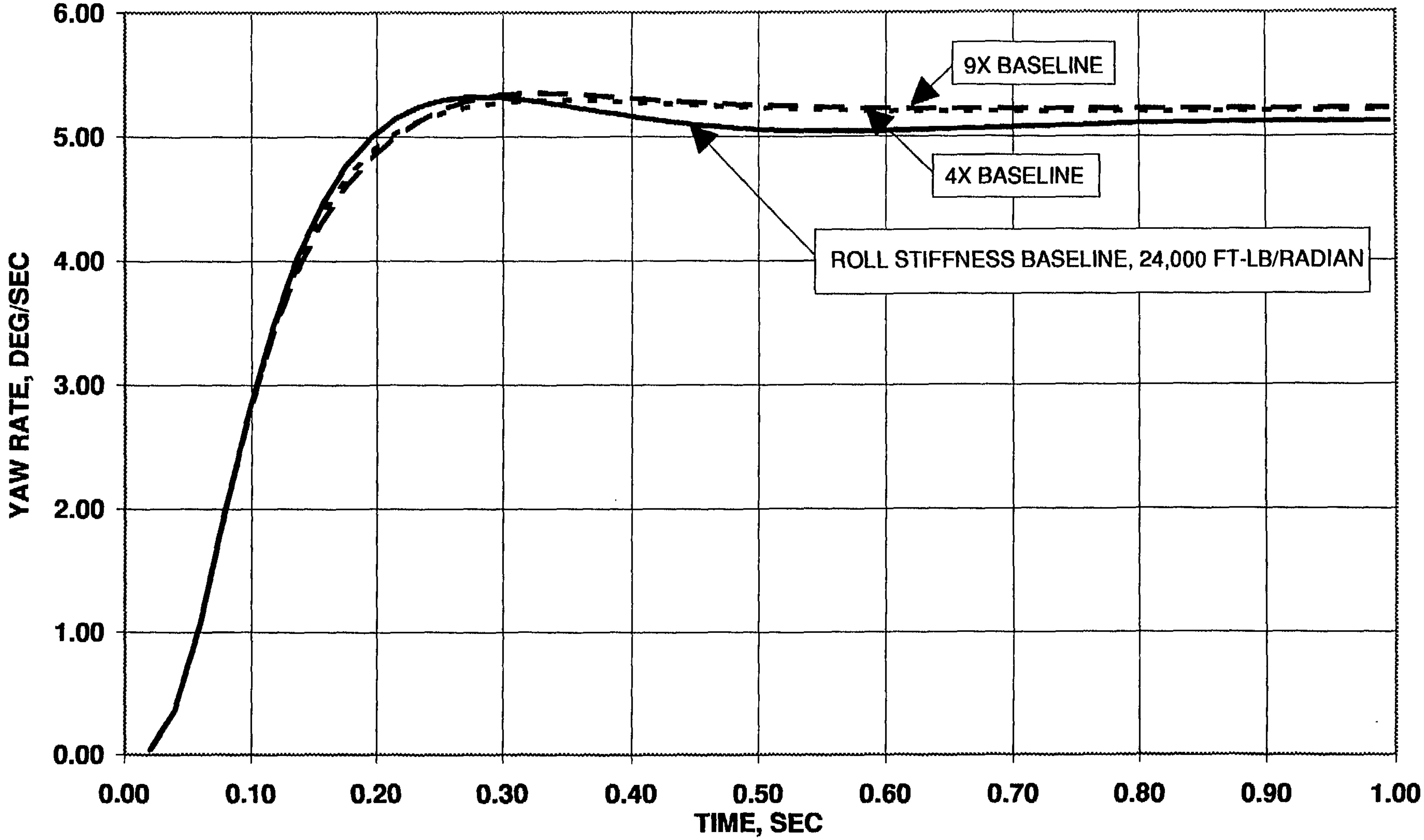


Chart 2-15. **EFF. OF ROLL DECOUPLING W/INCREASING ROLL STIFFNESS**
YAW RATE, 45 MPH

V610.XLS

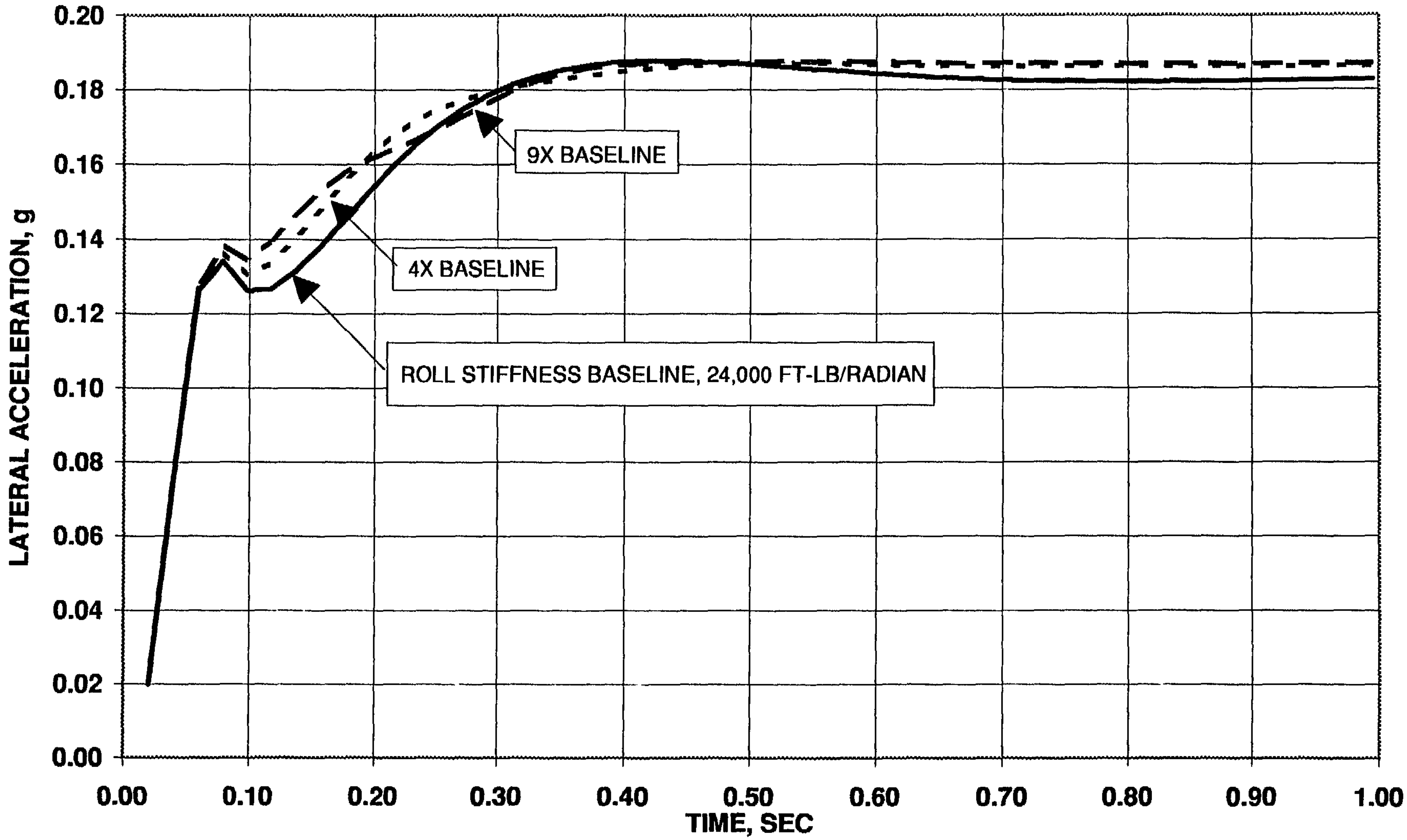


Chart 2-16. **EFF. OF ROLL DECOUPLING W/INCREASING ROLL STIFFNESS**
LATERAL ACCELERATION, 45 MPH

V610.XLS

Chart 2-17. Effect of Roll Decoupling

V610.XLS

ROLL STIFFNESS	ROLL DAMPING	SPEED MPH	UG DEG/g	ST. SENS. g/100°SWA	$^{\varphi}/Ay$ DEG/g	$^{\beta}/Ay$ DEG/g	RISE TIMES, SEC Ay	r	β	φ	PERCENT OVERSHOOT Ay	r	φ
75 MPH													
INCREASING ROLL FREQUENCY													
84,000	4,000	75	3.2	1.39	3.96	-1.10	0.24	0.10	0.29	0.34	7	29	10
320,000	8,400	75	3.0	1.43	1.05	-1.05	0.24	0.11	0.29	0.28	5	23	6
720,000	13,000	75	3.0	1.44	0.47	-1.03	0.24	0.11	0.33	0.25	5	22	5
VARIABLE ROLL DAMPING													
84,000	4,000	75	3.2	1.39	3.99	-1.10	0.24	0.10	0.29	0.34	7	29	10
84,000	1,650	75	3.1	1.39	4.08	-1.11	0.24	0.10	0.28	0.27	8	30	21
84,000	8,720	75	3.2	1.38	4.00	-1.04	0.24	0.10	0.29	0.36	7	28	7
45MPH													
INCREASING ROLL FREQUENCY													
84,000	4,000	45	3.1	0.91	4.00	0.38	0.22	0.15		0.33	3	11	4
320,000	8,400	45	3.0	0.93	1.05	0.44	0.19	0.15		0.14	0	2	1
720,000	13,000	45	2.9	0.93	0.46	0.46	0.22	0.16		0.08	0	3	2
VARIABLE ROLL DAMPING													
84,000	4,000	45	3.1	0.91	4.00	0.38	0.22	0.15		0.33	3	11	2
84,000	1,650	45	3.1	0.91	4.01	0.38	0.21	0.14		0.22	5	4	22
84,000	8,720	45	3.2	0.91	4.02	0.37	0.20	0.14		0.35	2	4	3

UG = UNDERSTEER GRADIENT

$^{\varphi}/Ay$ = ROLL GRADIENT (NEGATIVE)

$^{\beta}/Ay$ = SIDESLIP GRADIENT

Ay = LATERAL ACCELERATION

r = YAW RATE

β = SIDESLIP ANGLE

φ = ROLL ANGLE

2.18 Effect of Understeer on Lateral Acceleration Response

As shown in this chart, at 75 mph we are able to vary the understeer gradient from -.2 to +9.0 by various combinations of sideslip angle and lateral acceleration feedback to the front and rear wheels. Values of the feedback gains can be supplied if quested. MD1 will probably want the particular values when and if they begin feedback simulations.

As commonly occurs, increasing the understeer increases overshoot and oscillation. The oversteer case (understeer = ***-0.2*** deg/g) takes a very long time to settle and is underdamped, as expected.

2.19 Effect of Understeer on Yaw Rate Response

Chart 2-19 shows that similar but more pronounced results occur for the yaw rate response. More understeer yields less damping, more overshoot, and more oscillation.

2.20 Effect of Rise Time on Lateral Acceleration

By a combination of feedback of rate of change of slideslip angle and rate of change of yaw rate (Le., yaw acceleration), we can change the rise time for yaw rate and lateral acceleration without changing the steady state responses. Feedback of yaw acceleration is equivalent to changing the yaw inertia, and feedback of sideslip angle rate is equivalent to changing the vehicle mass. These changes are affected by using both front and rear steer to avoid extraneous changes to other terms in the equations of motion.

These curves were calculated for the condition specified in the RFP, that is. 0.15 g and 80 km/hr. The rise times are changed from 0.22 to 0.89 sec, corresponding to the required variation from 0.2 to 0.9 sec. Thus, we demonstrated that we can achieve the required values.

2.21 Effect of Rise Time on Yaw Rate Response

Chart 2-21's curve is the companion to the curve shown in Chart 2-20. The same conditions apply, but the yaw rate rise times are, as expected, somewhat shorter. The steady state yaw rate is the value corresponding to the steady state lateral acceleration of 0.15 g and the speed of 75 mph.

2.22 Effect of Steer Angle on Yaw Rate Response, 75 MPH, Understeer: 9.0 deg/g

In Chart 2-22 we wanted to show how well or how poorly constant values of feedback gains would "work' when the amplitude of the J-tum increases to near the limit. We chose a stressing case of high understeer gradient because the required gains are very high to change the baseline car by such a large amount The indicated result is that the response becomes more oscillatory when the steer angle is increased. This implies that we will probably need some gain programming, perhaps with lateral acceleration, to maintain

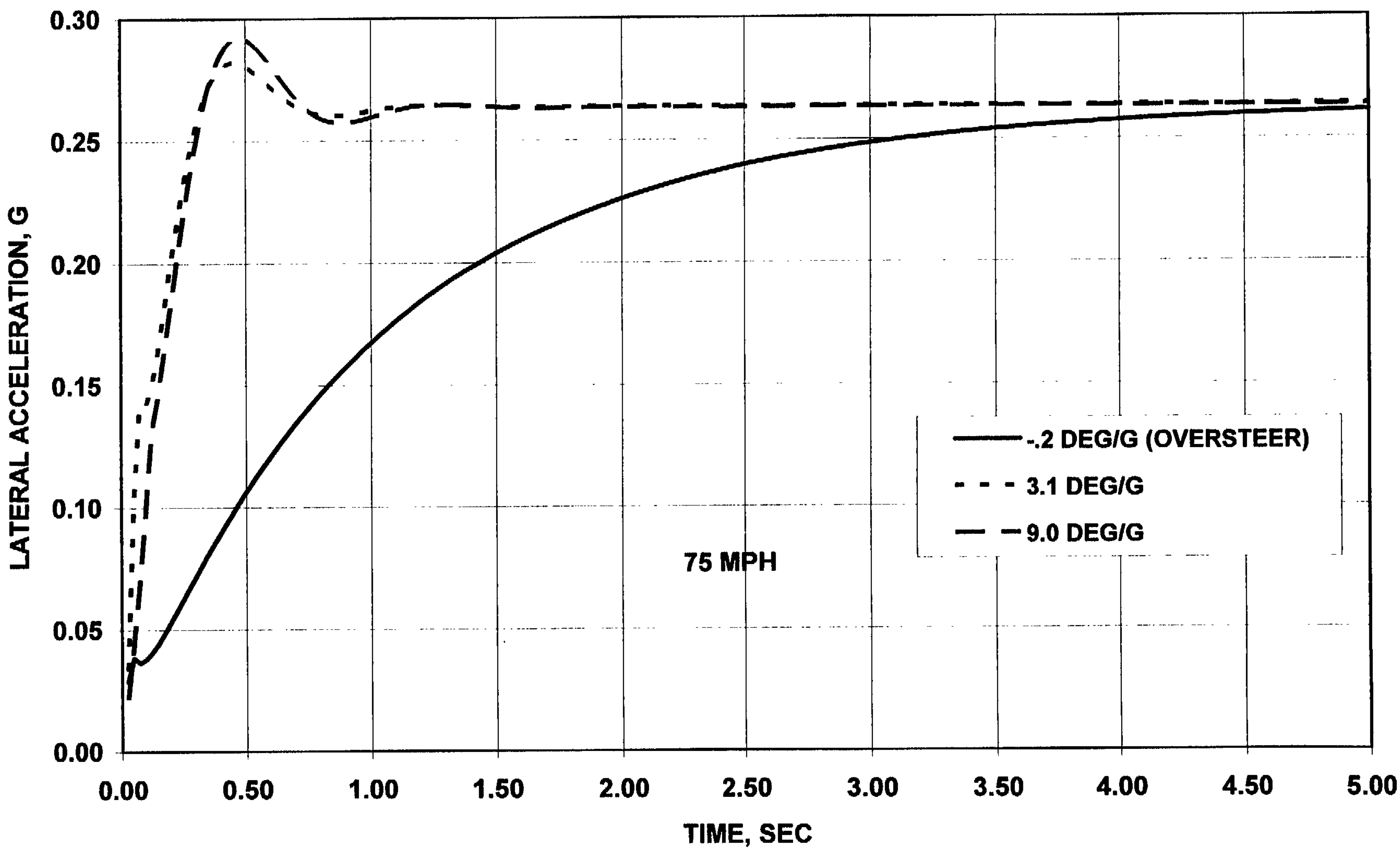


Chart 2-18. **EFF. OF UNDERSTEER ON LATERAL ACCELERATION RESPONSE**

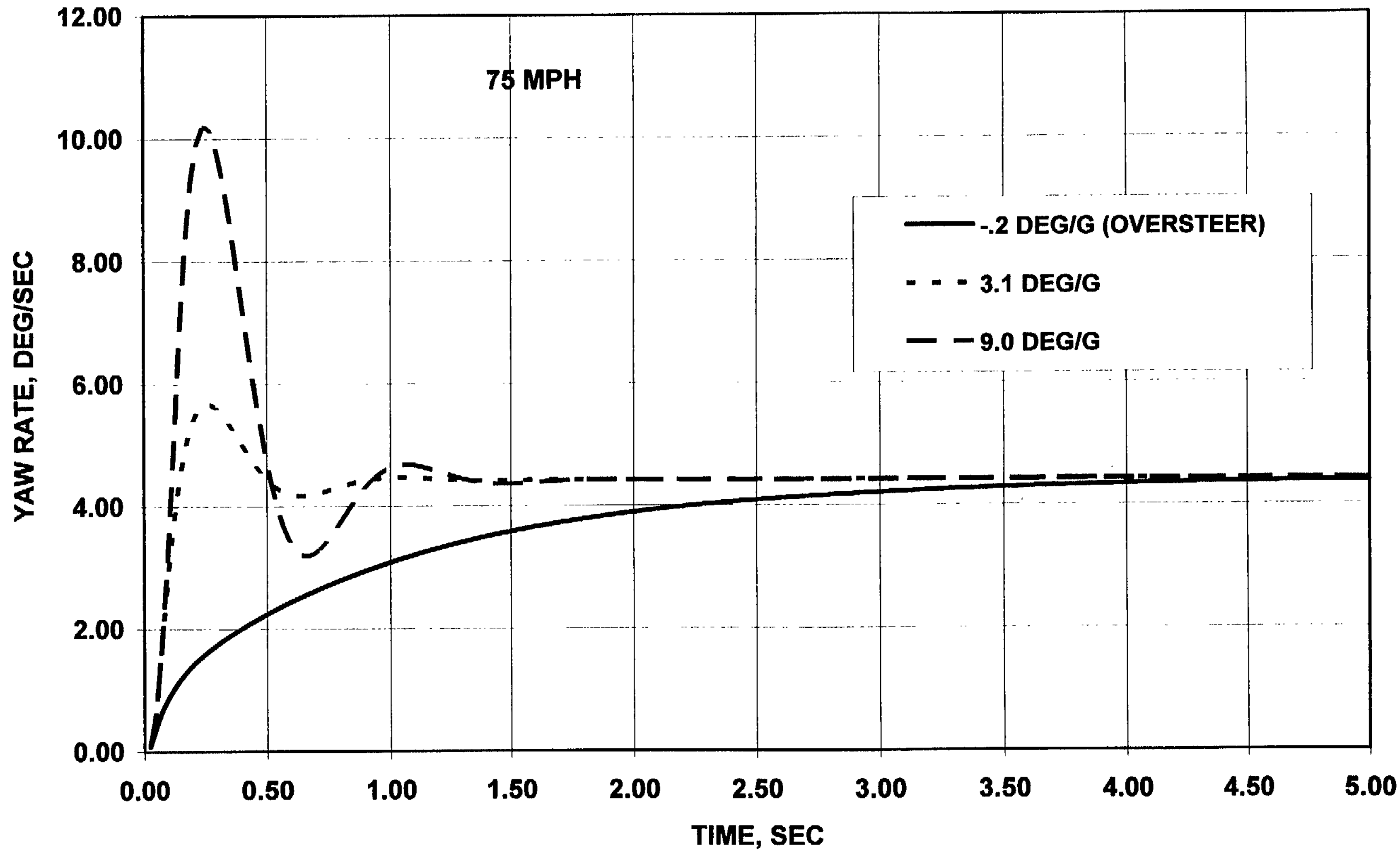


Chart 2-19. **EFFECT OF UNDERSTEER ON YAW RATE RESPONSE**

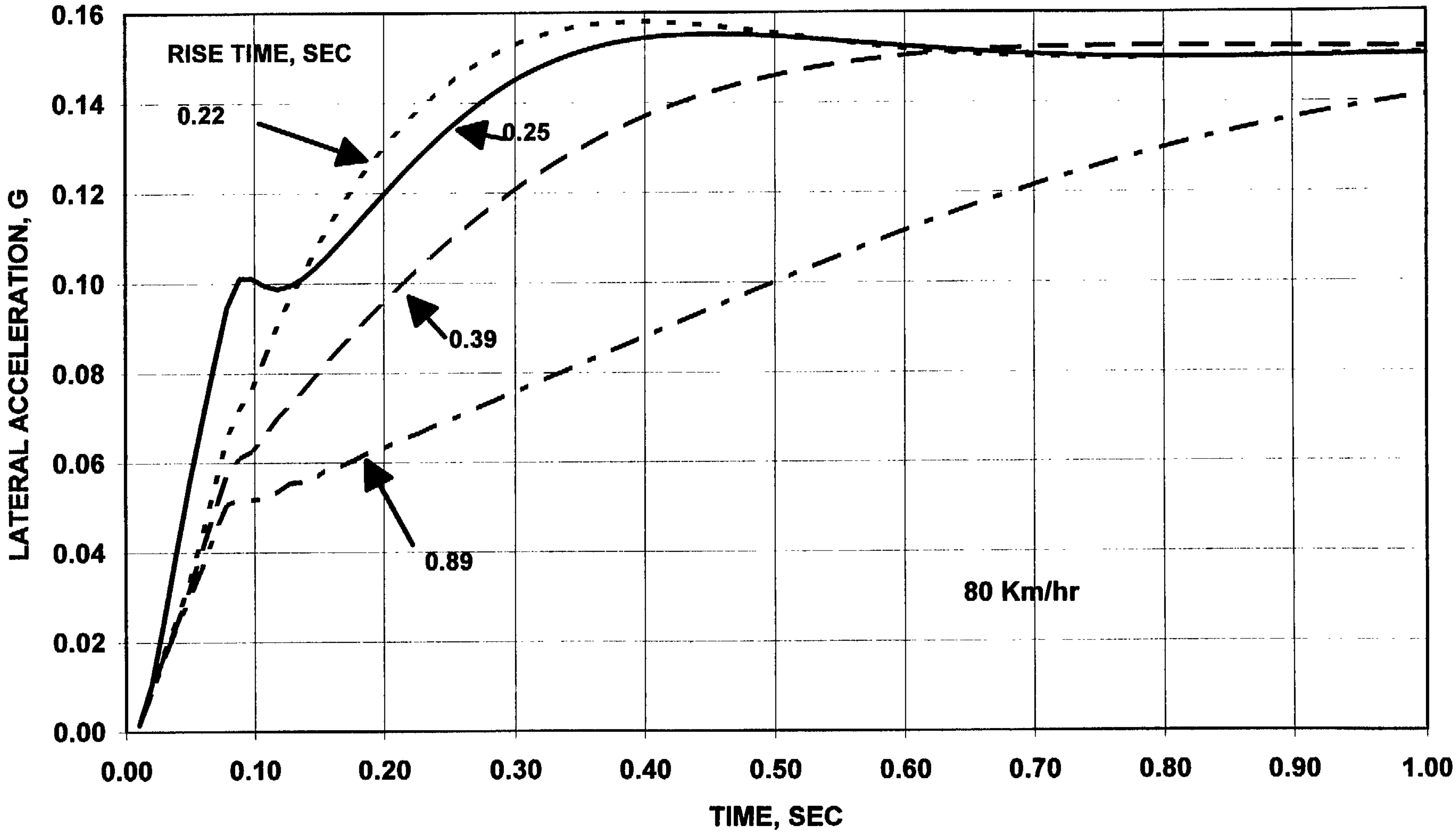


Chart 2-20. **EFFECT OF RISE TIME ON LATERAL ACCELERATION RESPONSE**

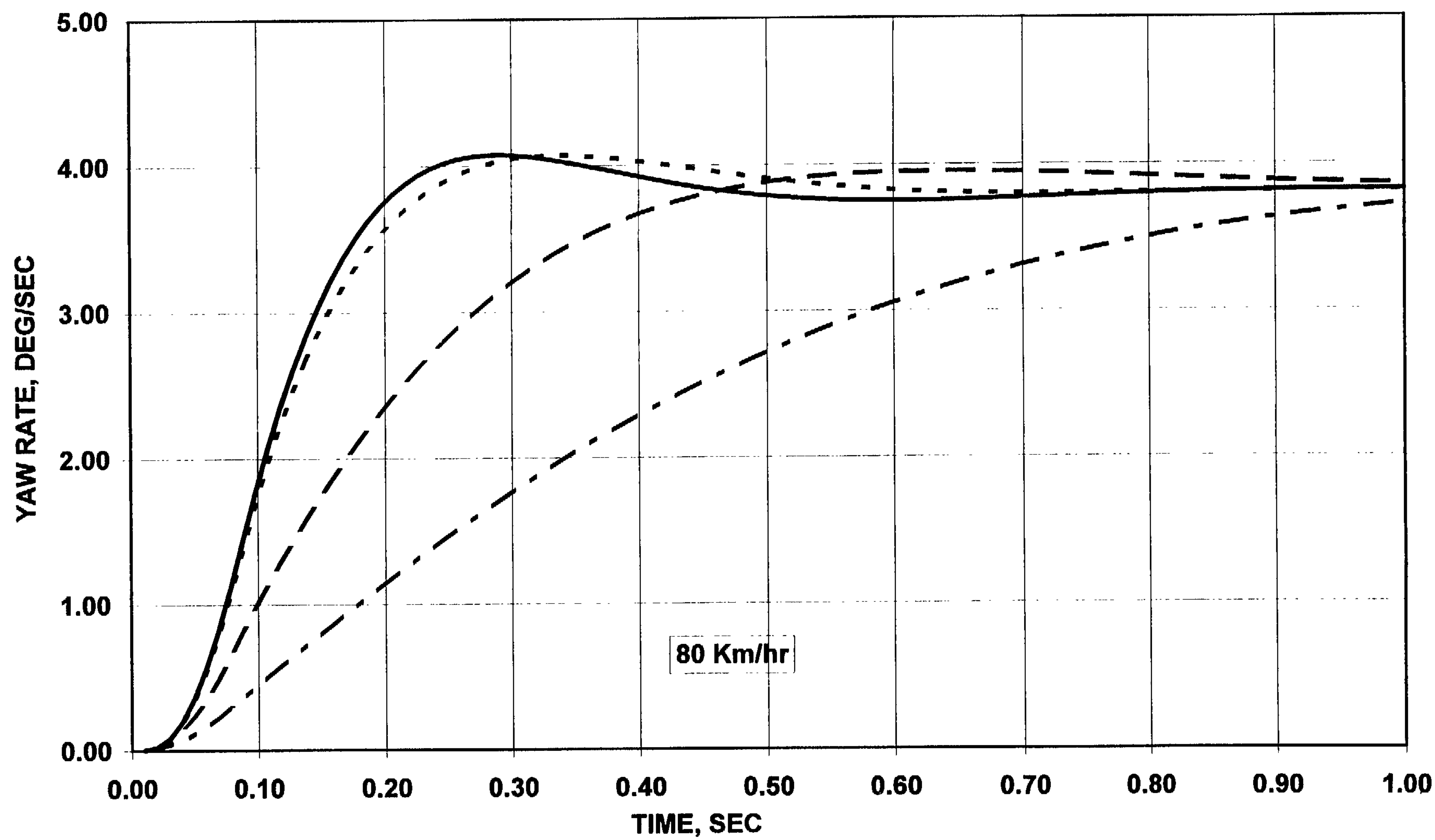


Chart 2-21. **EFFECT OF RISE TIME ON YAW RATE RESPONSE**

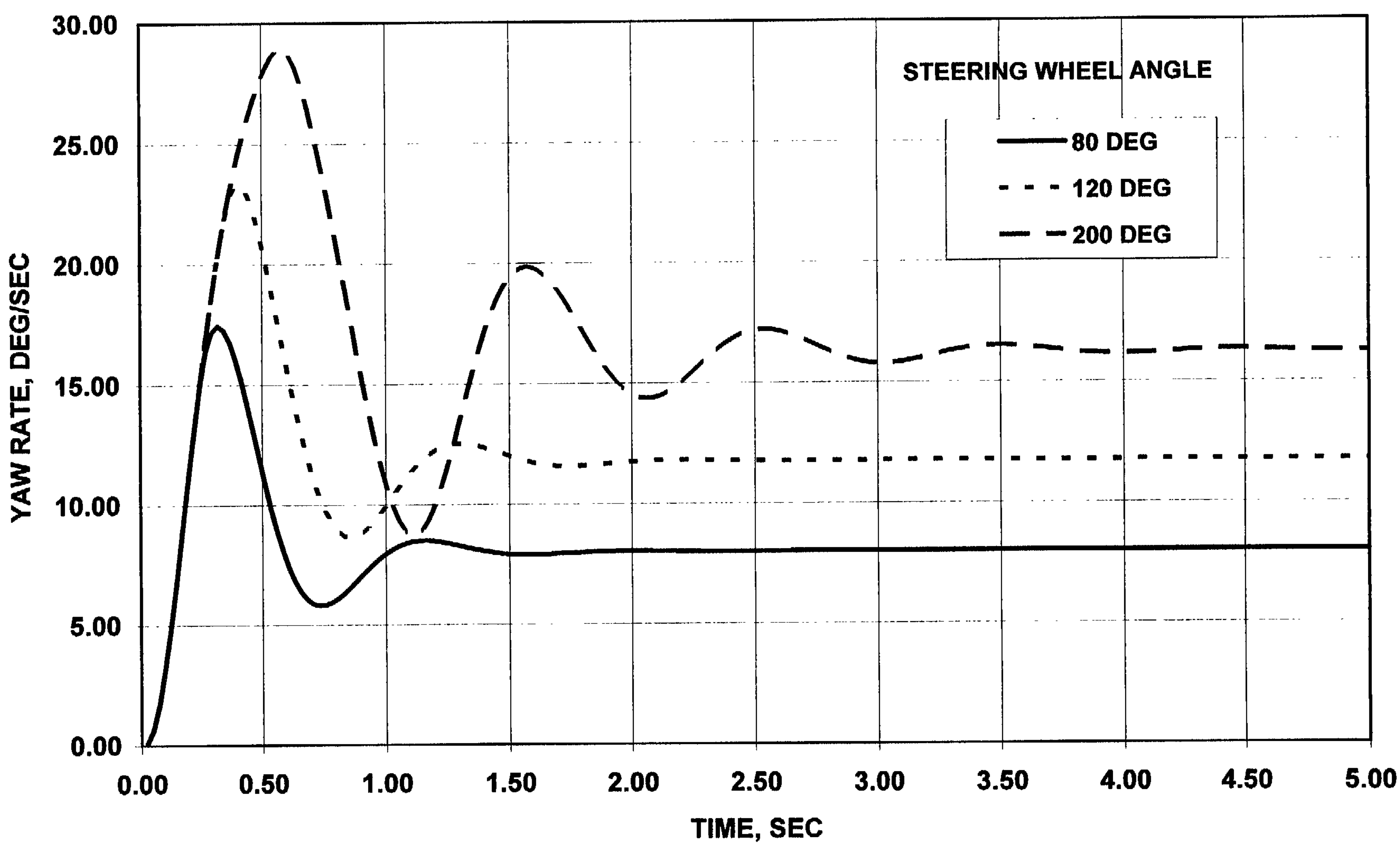


Chart 2-22. **EFFECT OF STEER ANGLE ON YAW RATE RESPONSE**

75 MPH, UNDERSTEER: 9.0 DEG/G

reasonably representative responses for large steer angles. This is especially true at the higher speeds. MDI will probably be investigating such gain programming.

The result also suggests that it will not be a simple matter to make the VDTV act like a car with excessive understeer over the complete range of speeds and steer amplitudes – from low speed to high speed and from low g to near the limit. Cain programming will certainly be needed, but the appropriate programming should be determined by a combination of simulations and on-road testing. It may be best to employ a model following adaptive system, as studied by Allan Lee; however, implementation of such an algorithm requires much simulation study and additional computing power. Basically, it is something to consider in the future.

2.23 Effect of Increasing Steer Angle on Lateral Acceleration, 75 MPH, Understeer: 9.0 deg/g

Chart 2-23 is a companion to Chart 2-22, but for the lateral acceleration responses. Again, some oscillatory behavior appears for the high-g maneuver. A maximum steady state lateral acceleration of 0.95 g is demonstrated, but this particular simulation does not necessarily yield accurate dynamics at high laterals. Note that this analysis uses the ZR tire, which has very high friction coeffkients. The tire data at high slip angles is well represented, but effects of lateral load transfer and roll axis drift are not accurately represented. (Lateral load transfer is included in its major effects; roll axis motion is not included.)

These runs were made with a fixed value of the steering ratio, so that the steering wheel angles appear to be quite large for the resulting lateral accelerations. This is typical of what happens when the understeer gradient is increased to such a large value (9.0 deg/g).

The simulation runs made to obtain these figures were also used to determine expected maximum values for the rear steer angle. For the various steer angles, the resulting rear steer angles are as follows:

steer angle, deg	80	120	200
maximum rear steer angle, deg	2.0	2.9	3.9

Hence, we expect the maximum required steer angle to be about 4.0 deg. However, this requirement is driven by the combination of the stressing high understeer and the large steer angle or high lateral acceleration. If it becomes difficult for Roush to accommodate this large of a rear steer angle, then we might consider restricting combinations of high under-steer and high steer angles.

2.24 Effect of Steer Bandwidth on Acceleration Response, 75 MPH, Understeer: 9.0 deg/g

We selected a very stressing case of high gains (needed to achieve the understeer of 9.0 deg/g) to investigate the bandwidth requirement on the front and rear steer subsystems. We considered bandwidths of l5, 20, and 30 Hz on the assumption that TRW could achieve a bandwidth of 20 Hz. If the value of 30 Hz were to produce a change in the responses, then we would suspect that a 20 Hz bandwidth is not sufficient.

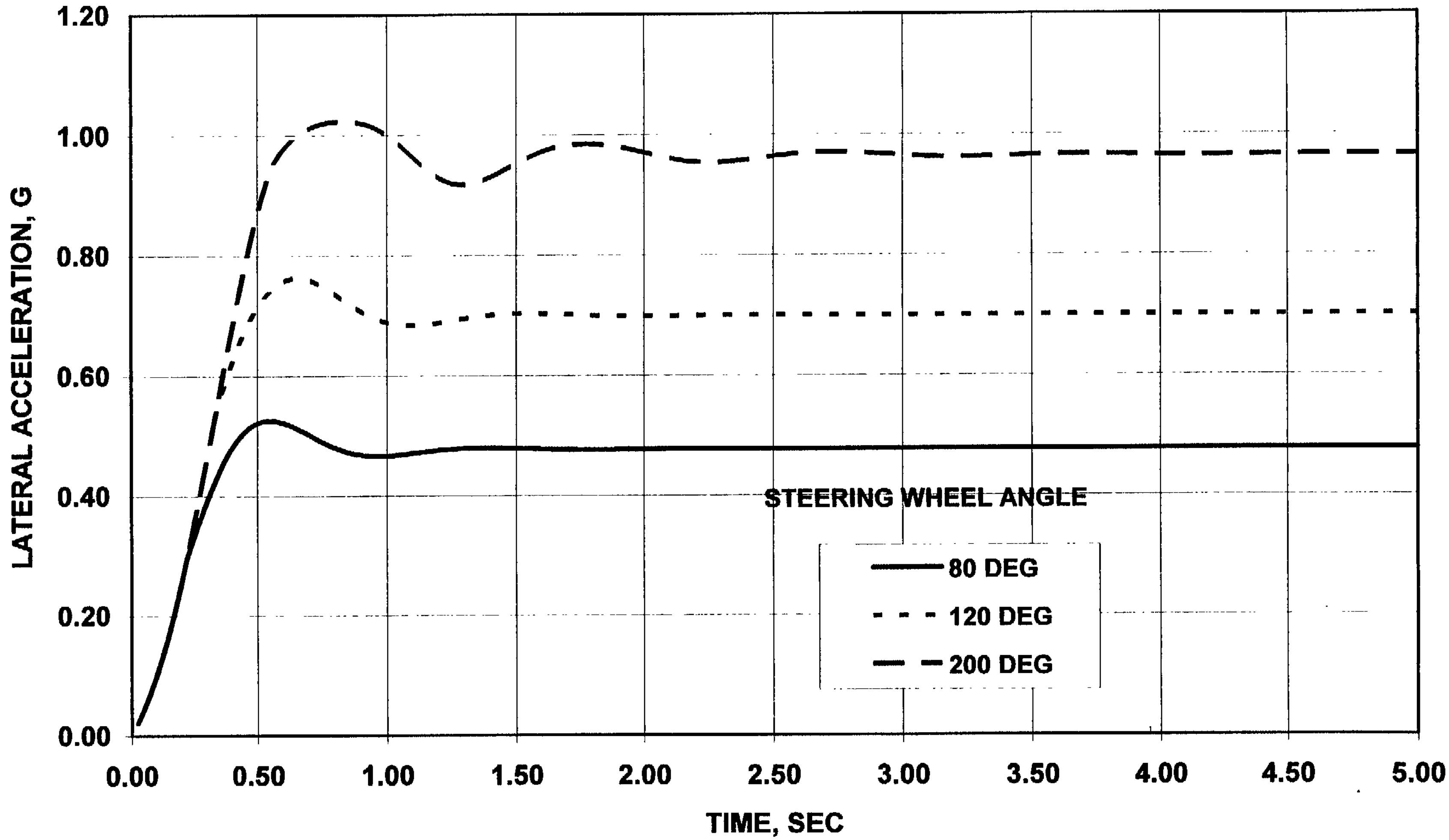


Chart 2-23. **EFFECT OF INCREASING STEER ANGLE ON LAT. ACC.**

75 MPH, UNDERSTEER: 9.0 DEG/G

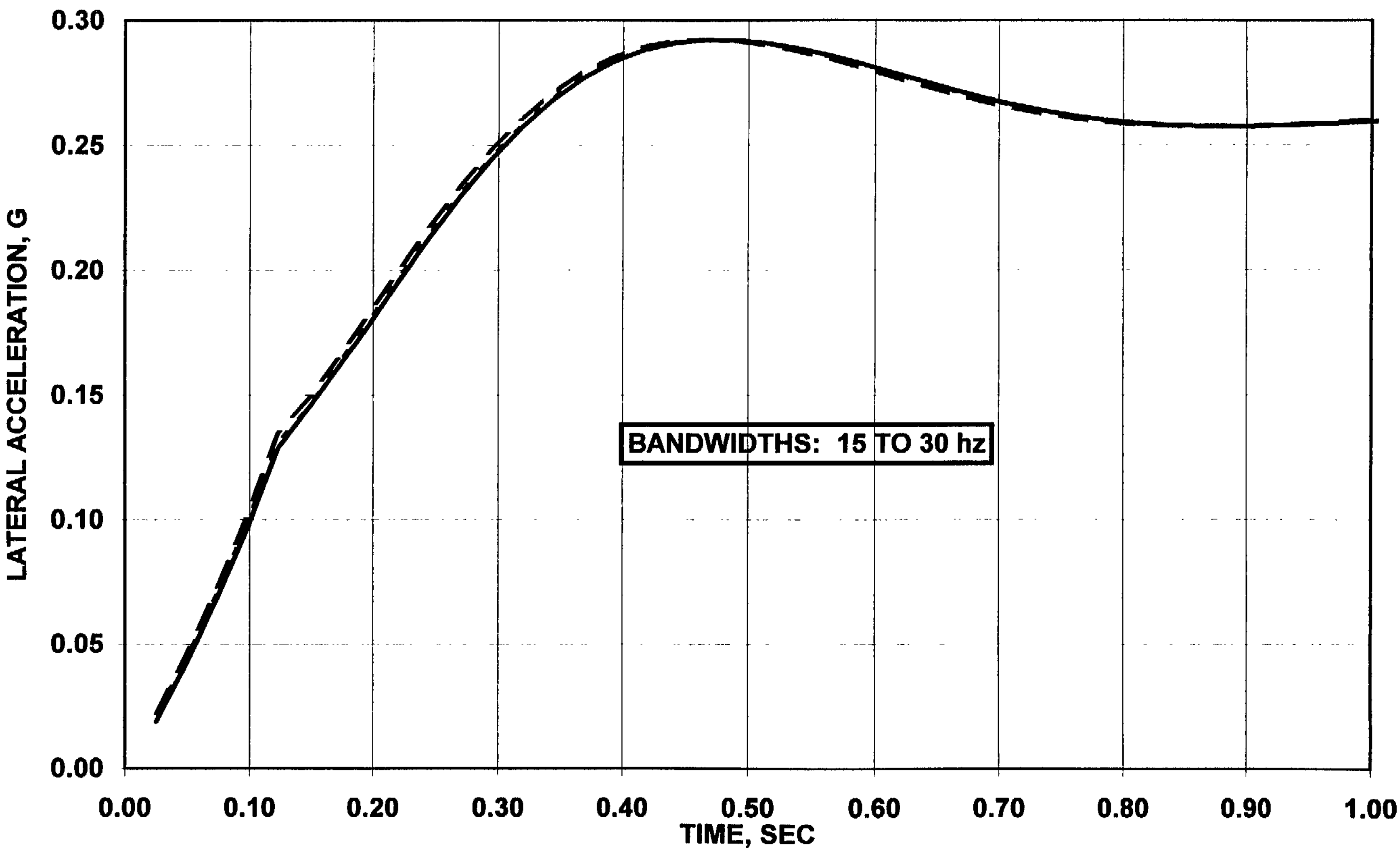


Chart 2-24. **EFFECT OF STEER BANDWIDTH ON ACCELERATION RESPONSE**
75 MPH, UNDERSTEER: 9.0 DEG/G

Such is not the case, as indicated by this chart and the next Indeed, there is little difference in the responses between the three bandwidths.

In each case, we assume the damping to be 70% of critical, so that the undamped natural frequency and bandwidth arc equal for the simple second order control dynamics that we simulated. In our simulation, we assume that the control system commands a rack or ballscrew position, rather than steering wheel angle. We further assume that there is compliance (i.e., a spring) between the rack and the steer angle. We ignore the dynamics of the wheel inertia acting on this spring, but we do take into account the effect of compliances in this manner.

2.25 Effect of Steer Bandwidth on Sideslip Response, 75 MPH, Understeer: 9.0 deg/g

Chart 2-25 is a companion to Chart 2-24. Here we demonstrate that sideslip angle response is often more sensitive to changes in the dynamics. Again, little change in response is indicated, despite the two-to-one change in bandwidth.

2.26 Varying Time to Peak Yaw Rate Response, 50 MPH, 0.4 g Steady State Lateral Acceleration

For an understeer gradient of 3.1 deg/g, we varied the feedback gains from sideslip angle rate and yaw acceleration (artificial mass and inertia) to change both the yaw overshoot and time to the peak response. We chose time to peak response because we have some data on the U.S. fleet for this metric. The goals, as determined from the fleet data are 0.2 to 0.9 sec. We achieved a variation from 0.22 to 0.89 sec to the peak yaw response.

2.27 Varying Yaw Overshoot, 50 MPH, 0.4g Steady State Lateral Acceleration

By feeding back yaw acceleration we are able to change the damping of the decoupled yaw-sideslip mode over a wide range, as shown in Chart 2-27. In fact, we can make the damping negative so that the vehicle becomes dynamically unstable, resulting in increasing oscillations. This chart shows responses with yaw rate overshoot values ranging from 2% to 58%. The goals we suggest, based on the U.S. fleet data, are from 0 to 40%. Hence, we demonstrate that we can cover such a range

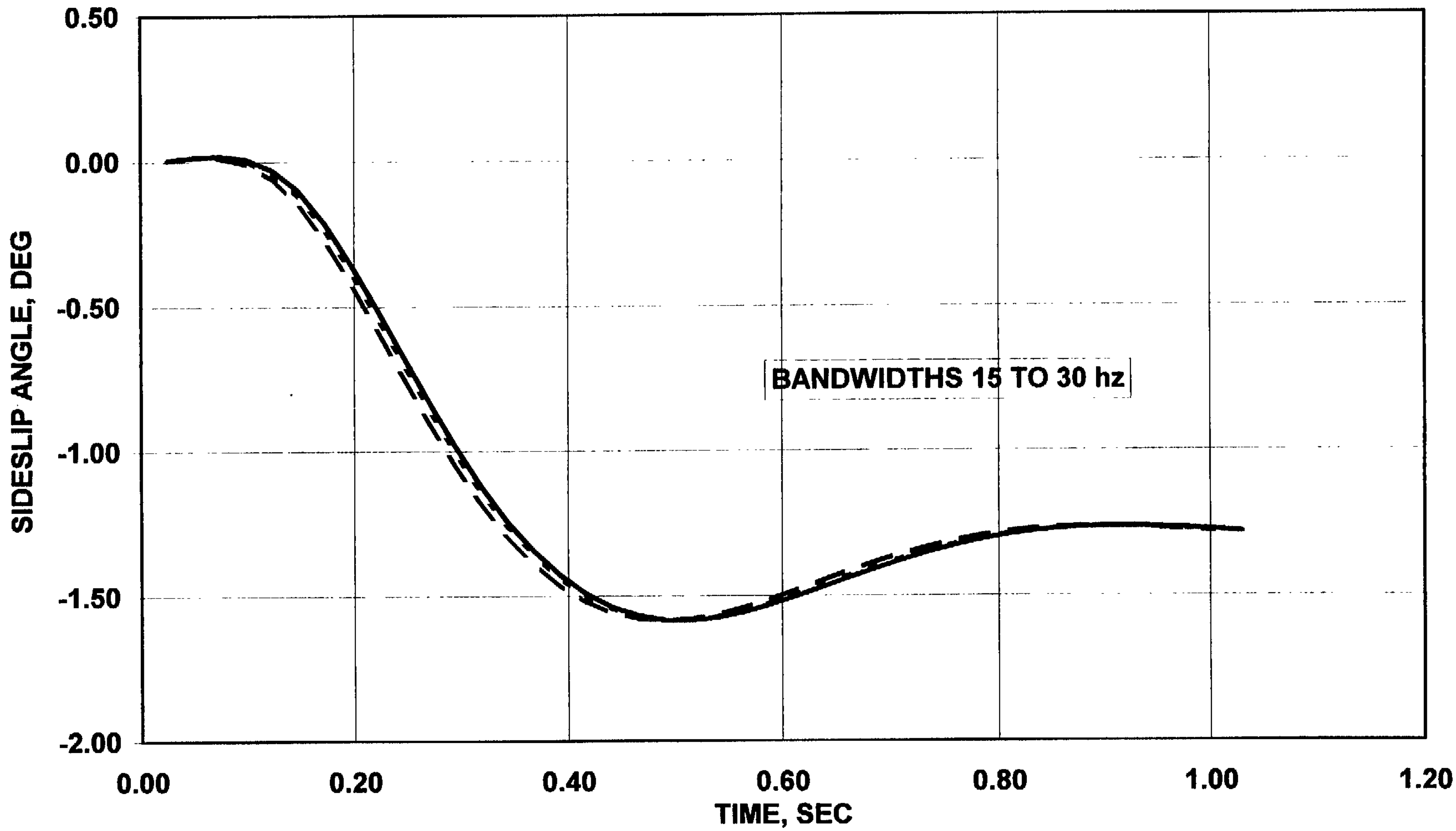


Chart 2-25. **EFFECT OF STEER BANDWIDTH ON SIDESLIP RESPONSE**

75 MPH, UNDERSTEER: 9.0 DEG/G

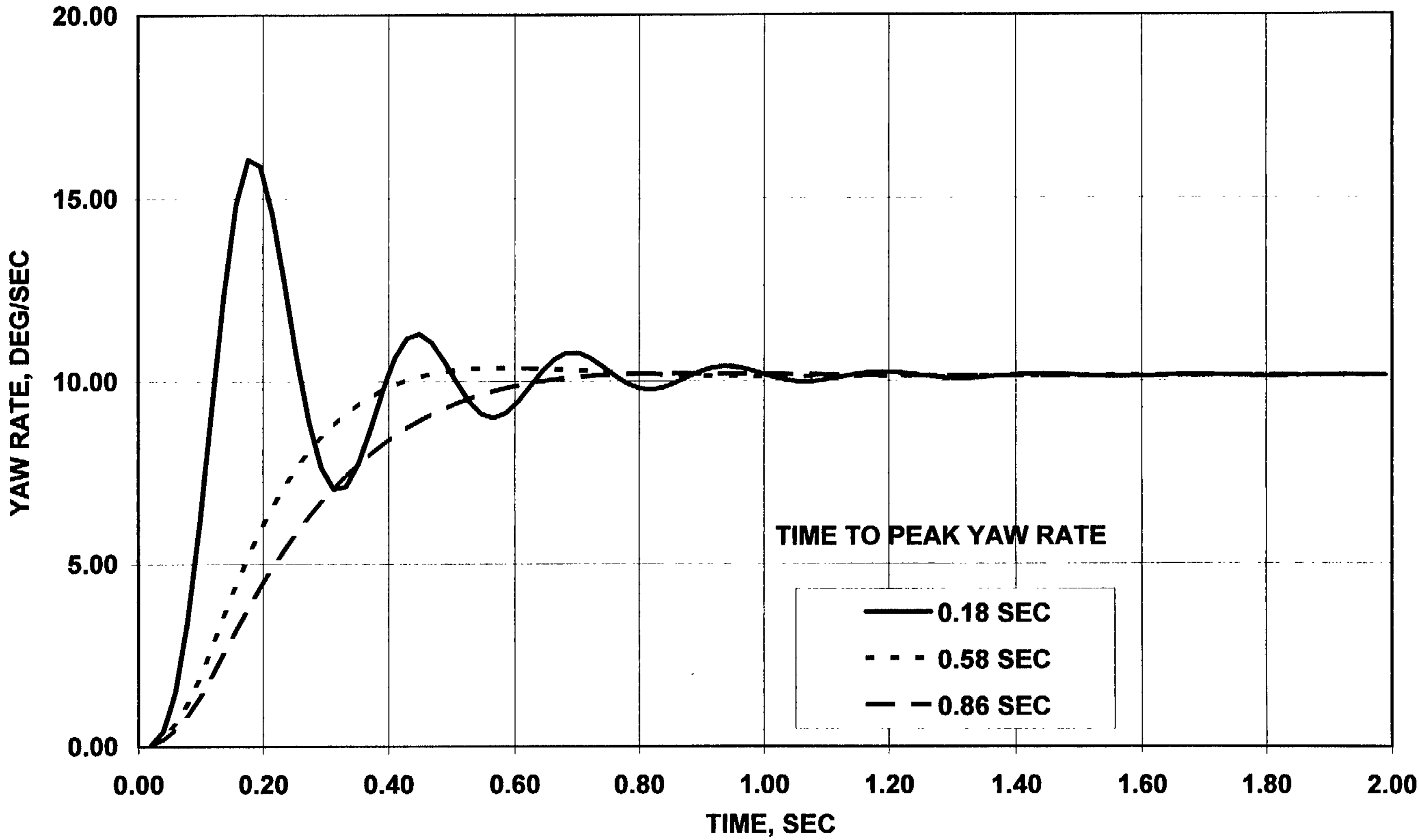


Chart 2-26. **VARYING TIME TO PEAK YAW RATE RESPONSE 50 MPH, 0.4G STEADY STATE LAT. ACC.**

VO3840.XLS

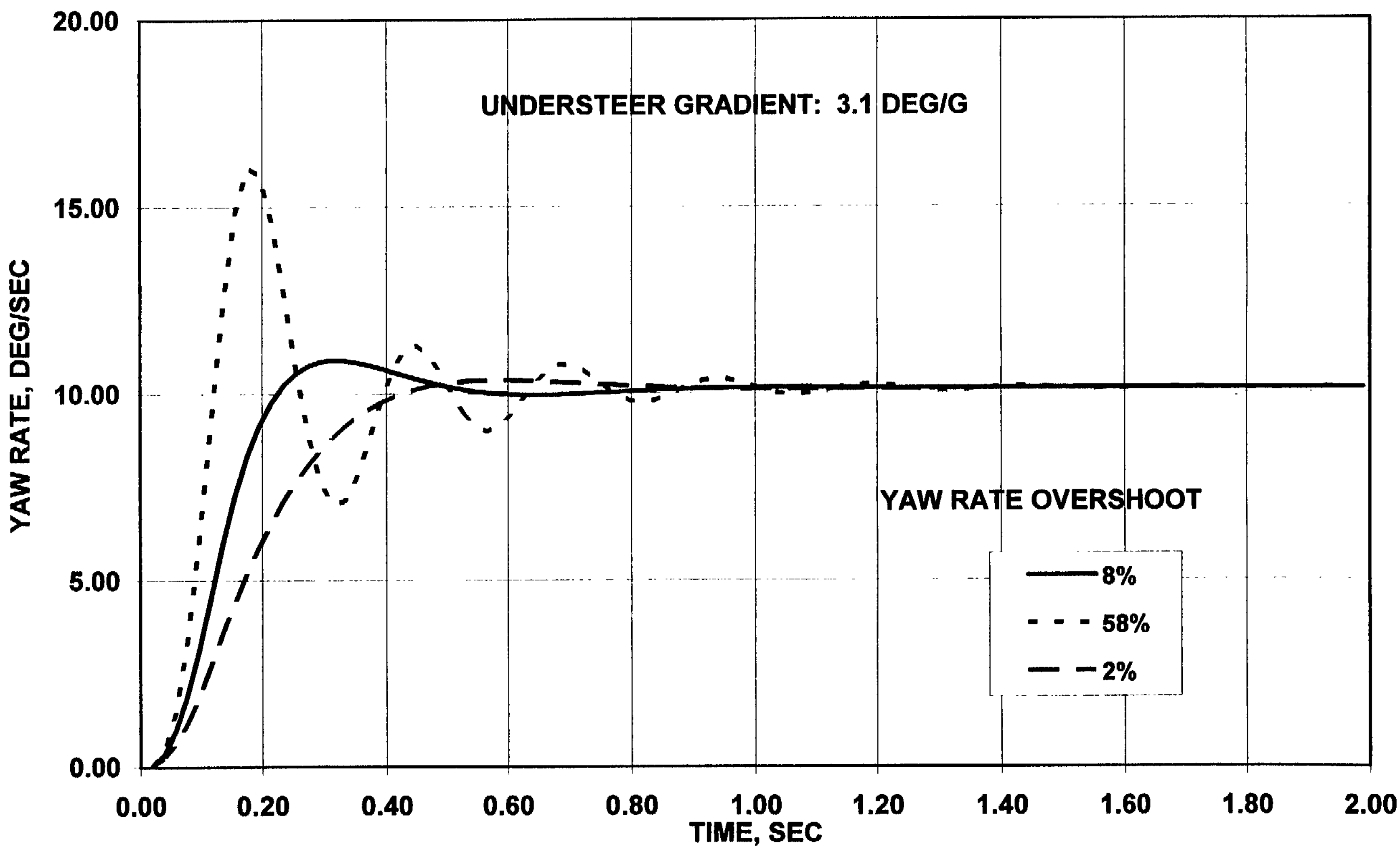


Chart 2-27. **VARYING YAW OVERSHOOT**
50 MPH, 0.4 G STEADY STATE LATERAL ACCELERATION

VO3739.XLS

2.28 Summary Comments

We have demonstrated that we can achieve both the RFP requirements on lateral acceleration rise time and understeer gradient and the goals that we determined from the U.S. fleet data for time to peak yaw rate, yaw-rate overshoot, and sideslip-angle gradient. Steering sensitivity is fully variable by simply changing the steering ratio by laptop computer. We also demonstrated that a steer subsystem bandwidth of 20 Hz should be adequate in the sense that responses are unaffected when we increase the bandwidth further. In addition, we found that the maximum rear steer angle to be 4 deg, but only for very stressing cases of high understeer and large steer angles.

Analysis has demonstrated that the roll response can be uncoupled from the yaw-sideslip response so that yaw rate and lateral acceleration can be varied independent of any changes to the roll degree of freedom.

It should be noted that further refinements in gain selection, gain programming with speed and steer amplitude, and so forth can be made, and we could consider the frequency response metrics that we were unable to complete due to time constraints (runs of frequency responses by frequency sweeps take up to 30 minutes on MRA's computer).

The concluding group of charts in this section provide reference data for the analyses conducted. These charts are numbered 2-28 through 2-32.

- 2-28 Increasing Steer Metric, Data From NHTSA Report
- 2-29 Frequency Domain Metrics, Data From NHTSA Report
- 2-30 J-Turn Metrics, Data From NHTSA Report
- 2-31 Summary of Simulated Vehicle Metrics (4 pages)
- 2-32 Summary From Ford-Provided Data (4 pages)

Chart 2-28. Increasing Steer Metric

Data From NHTSA Report

Sample - 21 Vehicles

Speed = 50 MPH

Lateral Acceleration	(g)	***Maximum Lateral Acceleration Gains x 100***	(g/100 deg)
Maximum	0.800	Maximum	1.180
Minimum	0.660	Minimum	0.730
Average	0.745	Average	0.897
Standard Deviation	0.034	Standard Deviation	0.141
Mean + 3σ	0.845	Mean + 3σ	1.320
Mean - 3σ	0.644	Mean - 3σ	0.474
Maximum + 25%	1.000	Maximum + 25%	1.475
Minimum - 25%	0.495	Minimum - 25%	0.548

Understeer Gradient @ .1g	(deg/g)	***Sideslip Gradient***	(deg/g)
Maximum	4.180	Maximum	-1.211
Minimum	0.420	Minimum	-5.835
Average	1.946	Average	-2.742
Standard Deviation	0.814	Standard Deviation	0.933
Mean + 3σ	4.388	Mean + 3σ	0.057
Mean - 3σ	-0.497	Mean - 3σ	-5.541
Maximum + 25%	5.225	Maximum + 25%	-1.514
Minimum - 25%	0.315	Minimum - 25%	-4.376

METRIC_3.XLS

Sample - 21 Vehicles

Speed = 25 Mph 50 Mph

Yaw Rate Bandwidth	(Hz)	(Hz)
Maximum	3.142	2.475
Minimum	1.983	1.158
Average	2.472	1.845
Standard Deviation	0.320	0.367
Mean + 3σ	3.433	2.947
Mean - 3σ	1.510	0.744
Maximum + 25%	3.927	3.094
Minimum - 25%	1.487	0.869

Lateral Acceleration Bandwidth	(Hz)	(Hz)
Maximum	1.533	0.925
Minimum	0.942	0.483
Average	1.132	0.708
Standard Deviation	0.148	0.114
Mean + 3σ	1.576	1.051
Mean - 3σ	0.688	0.365
Maximum + 25%	1.917	1.156
Minimum - 25%	0.706	0.362

Roll Angle Bandwidth	(Hz)	(Hz)
Maximum	3.808	1.183
Minimum	1.133	0.483
Average	1.918	0.883
Standard Deviation	0.753	0.181
Mean + 3σ	4.179	1.426
Mean - 3σ	-0.342	0.341
Maximum + 25%	4.760	1.479
Minimum - 25%	0.850	0.362

Sample - 21 Vehicles	Speed = 50 MPH	
	Lateral Acceleration = .4 g	*Lateral Acceleration = 75% of Maxiumum*
Sideslip Angle	Degrees	Degrees
Maximum for Sample	2.120	3.140
Minimum for Sample	0.790	1.410
Average for Sample	1.348	2.176
Standard Deviation	0.270	0.402
Mean + 3σ	2.158	3.381
Mean - 3σ	0.539	0.970
Maximum + 25%	2.650	3.925
Minimum - 25%	0.593	1.058

Yaw Rate	Percent	Percent
Maximum Percent Overshoot	25.42	33.50
Minimum Percent Overshoot	4.24	11.84
Average Percent Overshoot	12.24	19.65
Standard Deviation	4.68	5.83
Mean + 3σ	26.30	37.13
Mean - 3σ	-1.81	2.16
Maximum + 25%	31.77	41.87
Minimum - 25%	3.18	8.88

Yaw Rate Response Time	Seconds	Seconds
Maximum Peak Time	0.694	0.604
Minimum Peak Time	0.320	0.344
Average Peak Time	0.453	0.433
Standard Deviation	0.089	0.070
Mean + 3σ	0.720	0.643
Mean - 3σ	0.185	0.223
Maximum + 25%	0.868	0.755
Minimum - 25%	0.240	0.258

Summary of Simulated Vehicle Metrics

Chart 2-31.
Page 1.

METRIC_3 XLS

Vehicle Description			262	263	267	268	257	266	269	271	239	264	273	250	145	272	274	261	265	270	122	119	275
Vehicle Number			262	263	267	268	257	266	269	271	239	264	273	250	145	272	274	261	265	270	122	119	275
Model Year			1977	1982	1984	1984	1982	1983	1980	1983	1983	1987	1982	1987	1983	1985	1985	1989	1980	1984	1985	1987	1980
Make			Renault	Toyota	Honda	Honda	Honda	Nissan	Chevrolet	olkswage	Dodge	Datsun	B.M.W	Hyundai	Toyota	Nissan	Chevrolet	Ford	Datsun	Pontiac	Oldsmobil	Ford	Buick
Model			LeCar	Starlet	CRX	Civic HB	Civic 4dr	Sentra	Chevette	Jetta	Omni	510	320I	Excel	Camry	Stanza4dr	Cavalier	Escort	200SX	Fiero	Ciera	T'bird	LeSabre
Parameter Source			STI	STI	STI	STI	STI	STI	STI	STI	CPMD	STI	STI	CPMD	CPMD	STI	STI	STI	STI	STI	CPMD	CPMD	STI
Vehicle Configuration																							
M		(lb-sec	55 797	55.953	57.818	61.548	69.000	73.000	71.300	66.211	67.267	74.448	74.914	75.621	75.870	77.712	78.334	84.000	81.442	80.665	88.043	106.400	125.000
M		kg	816.665	818.948	846 245	900.839	1009.909	1068.455	1043.573	969.088	984.544	1089.646	1096.469	1106.816	1110.461	1137.421	1146.525	1229.455	1192.015	1180.642	1288.629	1557.309	1829.545
Increasing Steer Metrics	(mph)																						
Maximum Lateral Acceleration (Ay)	25.0	(g)	0.7000	0.7200	0.7800	0.7800	0.8000	0.6600	0.7100	0.7400	0.7700	0.7700	0.7200	0.7300	0.7600	0.7500	0.7100	0.7300	0.7900	0.7200	0.7600	0.7200	0.7400
Handwheel Angle @ Max Ay	25.0	(deg)	248 0300	168.0100	259.4300	282 0300	282 0300	238.6200	242.4300	248.6300	283.0300	252.6300	235.0200	254.6300	245.8300	215.2200	197.6200	260.0300	244.0300	204.0200	236.4200	206.6200	242.0300
Max load transfer (%)	25 0	(%)	73.9800	65 0200	58.8400	59.3700	66.9200	58.5200	65.2700	71.7400	58.9300	71.9800	71.9800	72.7200	64.9900	60.7900	60.8900	66.4500	59.3700	56.7000	54.3100	63.1800	58.5000
0.85*Ay Max			0.5950	0.6120	0.6630	0.6630	0.6800	0.5610	0.6035	0.6290	0.6545	0.6545	0.6120	0.6205	0.6460	0.6375	0.6035	0.6205	0.6715	0.6120	0.6460	0.6120	0.6290
0 100			0.100	0.100	0.100	0.100	0.100	0.100	0.100	0.100	0.100	0.100	0.100	0.100	0.100	0.100	0.100	0.100	0.100	0.100	0.100	0.100	0.100
Understeer Ay=0.1g	25.0	(deg/g)	1.5900	1.1200	2.0100	1.8200	1.9300	3.0500	2.2600	2.2500	1.9600	1.0200	1.3600	1.4700	1.2600	2.4100	3.0200	2.1100	2.9900	0.4500	1.9800	1.6300	4.2200
Ay=Max	25.0	(deg/g)	63.6800	57.7300	54.1600	59.1700	66.7200	102.5000	47.8000	68.2800	54.6500	31.0000	18.2100	49.6400	55.7400	62.4600	71.6700	79.9000	40.0100	53.5700	61.7600	72.6900	22.2600
Min (Ay<85% Max)	25.0	(deg/g)	1.5800	1.0900	2.0000	1.8200	1.9200	2.9800	2.2400	2.1800	1.9600	1.0100	1.3500	1.4400	1.2000	2.4000	3.0200	2.0700	2.9800	0.4400	1.9600	1.5900	3.9300
Max (Ay<85% Max)	25.0	(deg/g)	9.1300	8.7100	7.6600	7.6700	8.6500	16.4500	12.3000	4.2700	7.5900	12.6000	7.7100	7.1700	9.6200	8.3600	12.4400	14.8400	7.9400	6.8900	6.8900	11.5500	15.5400
Max Grad(Ay<85%)	25.0	(deg)	97.4200	95.5500	66.2200	67.0100	83 8200	170 6700	105.6800	25.2300	65.8900	98.6000	62.3800	80.9000	105.5600	84.6600	110.6300	131.4800	60.2000	75.3400	96.3100	107.5300	98.7200
SS Gains Ay=0.2g Yaw Rate	25.0	(1/sec)	0.1700	0.2380	0.1770	0.1790	0.1720	0.1930	0.1810	0.1700	0.1580	0.1770	0.1790	0.1730	0.1950	0.2030	0.2240	0.1890	0.1790	0.2110	0.1860	0.2220	0.1760
Sideslip	25 0	(--)	0.0087	0.0079	0.0084	0.0086	0.0090	0.0102	0.0068	0.0080	0.0072	0.0024	0.0071	0.0087	0.0080	0.0107	0.0147	0.0080	0.0115	-0.0053	0.0097	0.0128	0.0084
Load Trans	25.0	(%/deg	0 3490	0.4160	0.2610	0.2690	0.2830	0.3390	0 3230	0.3160	0.2400	0.3110	0.3420	0.3360	0.3220	0.3310	0.3770	0.3380	0.2640	0.3240	0.2680	0.3740	0.2660
Ay	25.0	(g/deg)	0 0034	0.0047	0.0035	0 0036	0 0034	0.0039	0.0038	0 0034	0.0032	0 0035	0.0036	0.0035	0.0039	0.0041	0.0045	0.0038	0.0036	0.0042	0 0037	0.0044	0.0035
Ay=85% Ma Yaw Rate	25 0	(1/sec)	0.1700	0.2320	0.1780	0.1750	0.1720	0.1800	0.1740	0.1770	0.1580	0.1800	0.1710	0.1670	0.1650	0.2060	0.2180	0.1780	0.1820	0.2090	0.1880	0.2120	0.1720
Sideslip	25.0	(--)	0 0067	0 0050	0 0063	0.0062	0.0043	0.0058	0.0020	0.0046	0.0050	-0.0003	0.0041	0.0060	0 0056	0.0073	0.0119	0.0056	0.0096	-0.0087	0.0071	0.0081	0.0049
Load Trans	25 0	(%/deg	0 3520	0 4110	0.2840	0 2650	0.2840	0.3140	0.3140	0.3300	0.2400	0.3270	0.3330	0.3280	0.3100	0.3310	0.3670	0.3190	0.2710	0.3280	0.2690	0.3640	0.2640
Ay	25.0	(g/deg)	0.0034	0.0048	0 0035	0.0035	0.0034	0.0038	0 0034	0.0035	0.0031	0.0038	0.0034	0.0033	0.0037	0.0041	0.0043	0.0035	0.0036	0.0042	0.0037	0.0042	0.0034
Maximum Lateral Acceleration (Ay)	50 0	(g)	0.7000	0.7300	0.7900	0.7700	0 8000	0 6600	0.7300	0.7400	0.7600	0.7600	0.7400	0.7200	0.7600	0.7500	0.7100	0.7300	0.8000	0.7300	0.7500	0.7400	0.7500
Handwheel Angle @ Max Ay	50.0	(deg)	127.6100	95 4200	143 0100	128.6100	153.0100	146.6100	139.4100	121.6100	139.6100	127.6100	100.0200	120.4100	121.0100	112.0100	110.0100	149.0100	126.6100	93.2200	118.0100	111.4100	118.0100
Max load transfer (%)	50 0	(%)	73 9900	66.1800	59.1900	59.1700	66.7600	58.4600	67.8900	71.5800	58.8000	73.0300	73.4600	72.7800	65.3400	60.4900	60.9900	66.6200	60.0800	58.0600	54.1300	64.9000	58.0400
0.85*Ay Max			0.5950	0.6205	0.6715	0.6545	0.6800	0.5610	0.6205	0.6290	0.6460	0.6630	0.6290	0.6120	0.6460	0.6375	0.6035	0.6205	0.6800	0.6205	0.6375	0.6290	0.6375
0.100			0.100	0.100	0.100	0.100	0.100	0.100	0.100	0.100	0.100	0.100	0.100	0.100	0.100	0.100	0.100	0.100	0.100	0.100	0.100	0.100	0.100
Understeer Ay=0.1g	50 0	(deg/g)	1.5700	1.1100	1.9800	1.8100	1.9200	3.0100	2.2100	2.2600	1.9500	0.9800	1.3100	1.4400	1.2400	2.4200	3.0200	2.0900	2.3600	0.4200	1.9700	1.6100	4.1800
Ay=Max	50.0	(deg/g)	62 3800	56.8900	79.5800	56.3700	73.3800	101.1200	34.8800	68.3000	57.5200	23.7200	12.3300	49.9100	54.9100	64.4200	71.1900	73.7400	58.2200	52.4300	60.7500	72.7200	15.8500
Min (Ay<85% Max)	50.0	(deg/g)	1.5000	0.9500	1.9800	1.8000	1.9100	2.9300	2.1900	2.2200	1.9400	0.9400	1.2500	1.4100	1.1200	2.2600	2.8400	1.9300	2.3600	0.4100	1.8600	1.3800	3.8300
Max (Ay<85% Max)	50.0	(deg/g)	8.7700	8.2400	7.8800	7.3800	8.9100	16.1300	12.4800	4.9100	7.5000	11.0300	6.7100	6.7900	9.3800	8.3800	11.9700	14.3400	7.6600	5.9500	8.6600	10.9900	12.6800
Max Grad(Ay<85%)	50.0	(deg)	85.9300	81.4200	69.3300	64.4000	81.7400	155.2100	104.0100	27.1100	65.2100	71.1200	46.0100	62.4700	66.4500	74.9800	99.4100	122.4300	60.9700	66.4400	76.5900	100.2100	57.9600
SS Gains Ay=0.2g Yaw Rate	50.0	(1/sec)	0.2000	0.3090	0.2050	0.2280	0.1990	0.2050	0.2050	0.2010	0.1940	0.1940	0.2520	0.2360	0.2640	0.2340	0.2480	0.2150	0.2090	0.2940	0.2210	0.2790	0.1920
Sideslip	50.0	(--)	-0.0183	-0.0313	-0.0195	-0.0229	-0.0167	-0.0199	-0.0201	-0.0221	-0.0211	-0.0290	-0.0264	-0.0208	-0.0306	-0.0255	-0.0232	-0.0237	-0.0132	-0.0496	-0.0243	-0.0220	-0.0238
Load Trans	50.0	(%/deg	0.7990	1.0330	0.5890	0.6650	0.6380	0.6990	0.7100	0.7220	0.5720	0.6440	0.9310	0.6900	0.6380	0.7330	0.8040	0.7400	0.6060	0.8400	0.6130	0.9040	0.5600
Ay	50.0	(g/deg)	0.0078	0.0118	0.0080	0.0088	0.0078	0.0080	0.0079	0.0078	0.0075	0.0073	0.0097	0.0092	0.0101	0.0090	0.0096	0.0083	0.0082	0.0109	0.0085	0.0108	0.0074
Ay=85% Ma Yaw Rate	50.0	(1/sec)	0.2000	0.2900	0.2040	0.2140	0.1950	0.1760	0.1860	0.2140	0.1910	0.2040	0.2270	0.2140	0.2300	0.2350	0.2310	0.1860	0.2160	0.2970	0.2240	0.2500	0.1860
Sideslip	50.0	(--)	-0.0242	-0.0393	-0.0254	-0.0280	-0.0273	-0.0252	-0.0305	-0.0330	-0.0271	-0.0399	-0.0331	-0.0259	-0.0340	-0.0348	-0.0284	-0.0260	-0.0195	-0.0654	-0.0325	-0.0324	-0.0313
Load Trans	50.0	(%/deg	0.8250	1.0190	0.6060	0.6460	0.6420	0.6120	0.6650	0.7880	0.5800	0.7310	0.8750	0.8370	0.7690	0.7520	0.7740	0.6640	0.6400	0.9100	0.6390	0.8500	0.5620
Ay	50.0	(g/deg)	0.0079	0.0114	0.0081	0.0085	0.0077	0.0069	0.0073	0.0084	0.0075	0.0080	0.0089	0.0084	0.0091	0.0092	0.0091	0.0074	0.0085	0.0116	0.0089	0.0099	0.0073
Frequency Domain Metrics																							
Yaw Rate Bandwidth	25.0	(Hz)	3.142	2 717	2.517	2.542	2.767	2.658	2.663	2.100	2.175	2.300	2.600	2.642	2.450	2.100	2.133	2.650	2.925	2.233	2.133	2.258	1.983
Peak Frequency	25.0	(Hz)	1.692	1.542	1.458	1.450	1.533	1.458	1.533	0.000	0.875	0.000	1.367	1.450	1.258	1.008	0.000	1.458	1.692	0.883	0.733	1.258	0.000
Peak Freq Gain Ratio	25.0	(--)	1.273	1.152	1.101	1.085	1.198	1.204	1.287	1.000	1.048	1.000	1.107	1.141	1.080	1.039	1.000	1.145	1.170	1.072	1.055	1.074	1.000
Freq @ 180 Phase Shift	25.0	(Hz)	0 000	0 000	0.000	0 000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
180 Deg Gain Ratio	25.0	(--)	0.000	0.000	0 000	0.000	0.000	0 000	0 000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0 000	0 000
Load Transfer Bandwidth	25.0	(Hz)	1.650	1 625	1.625	1.725	1.725	1.550	1.683	1.417	3.458	1.317	1.492	1.525	1.625	1.333	3.858	1.625	1.958	1.167	1.517	1.483	1.333
Peak Frequency	25 0	(Hz)	0 992	1.000	0.875	0 875	1.092	0.883	1.092	0.717	0.717	0.000	0.883	0.975	0.875	0.725	2.642	0.992	1.250	0.000	0.725	0.867	0.000
Peak Freq Gain Ratio	25.0	(--)	1.521	1.183	1.140	1 126	1.324	1.347	1.421	1.084	1.062	1.000	1.231	1.339	1.164	1.107	1.179	1.247	1.346	1.000	1.086	1.120	1.000
Freq @ 180 Phase Shift	25.0	(Hz)	0.000	0 000	0 000	0.000	0.000	0 000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0 000	0.000
180 Deg Gain Ratio	25.0	(--)	0 000	0 000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Ay Bandwidth	25.0	(Hz)	1.100	1 283	1.267	1.317	1 342	1 042	1.225	0.958	1.108	0.992	1.092	1.075	1.108	0.942	1.050	1.133	1.533	0 992	1.042	1.158	1.017
Peak Frequency	25.0	(Hz)	3.950	3.850	3 850	3.950	3.950	3.650	3.850	4.042	3.417	3.658	4.042	3.650	3.383	3.725	3.650	3.725	4.042	4 617	3.200	3.508	3 233
Peak Freq Gain Ratio	25.0	(--)	3.039	1.569	1.748	1.576	1.782	2.253	1.923	2.794	1 659	1.755	2.294	2 581	1.854	2.256	3.057	2.205	2.005	1.209	1.628	1.920	1.546
Freq @ 180 Phase Shift	25.0	(Hz)	0 000	0 000	0.000	0 000	0.000	0.000	0.000	0 000	0.000	0.000	0.000	0.000	0 000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0 000
180 Deg Gain Ratio	25.0	(--)	0 000	0 000	0 000	0.000	0.000	0 000	0 000	0.000	0.000	0.000	0 000	0.000	0.000	0.000	0.000	0.000	0.000	0 000	0.000	0 000	0 000
Roll Angle Bandwidth	25.0	(Hz)	1.642	1 587	1 625	1.717	1.683	1.492	1 617	1.342	3.283	1.308	1.450	1.525	1.600	1.250	3.808	1.625	1.933	1.133	2.892	3.092	2.700
Peak Frequency	25.0	(Hz)	0.992	0 892	0 875	0 875	1 008	0 875	1.008	0.708	0.717	0.000	0 867	0.983	0 875	0 000	2.642	0.992	1 167	0.000	0 725	0.983	0 725
Peak Freq Gain Ratio	25 0	(--)	1 497	1.174	1 138	1.121	1.289	1.314	1 397	1.068	1.070	1.000	1.205	1.333	1.164	1.000	1.157	1.251	1.325	1.000	1.109	1.197	1.086
Freq @ 180 Phase Shift	25.0	(Hz)	3.908	3.900	3 933	4.025	3.850	3.558	3.775	4 167	3.533	3.675	4.075	3 733	3.475	3.775	3.717	3.717	4 058	4.417	3 258	3.567	3 417
180 Deg Gain Ratio	25.0	(--)	0.371	0.357	0.488	0.476	0.433	0.336	0.377	0.466	0.586	0.429	0.339	0.383	0.445	0.356	0.755	0.450	0.517	0.331	0.540	0 527	0.432

Summary of Simulated Vehicle Metrics

Chart 2-31.
Page 2.

METRIC_3.XLS

Vehicle Description																								
Vehicle Number					262	283	267	266	257	266	269	271	239	264	273	250	145	272	274	261	265	270	122	119	275
Model Year					1977	1982	1984	1984	1982	1983	1980	1983	1983	1987	1982	1987	1983	1985	1985	1989	1980	1984	1985	1987	1980
Make			--		Renault	Toyota	Honda	Honda	Honda	Nissan	Chevrolet	olkswage	Dodge	Datsun	B.M.W	Hyundai	Toyota	Nissan	Chevrolet	Ford	Datsun	Pontiac	Oldsmobil	Ford	Buick
Model					LeCar	Starlet	CRX	Civic HB	Civic 4dr	Sentra	Chevette	Jetta	Omni	510	320i	Excel	Camry	Stanza4dr	Cavalier	Escort	200SX	Fiero	Clera	T'bird	LeSabre
Parameter Source			-	-	STI	STI	STI	STI	STI	STI	STI	STI	CPMD	STI	STI	CPMD	CPMD	STI	STI	STI	STI	STI	CPMD	CPMD	STI
Vehicle Configuration																									
Side Slip	Peak Frequency		25.0	(Hz)	3.325	2.642	2.825	2.683	2.733	2.733	2.867	3.383	2.642	2.692	3.158	2.950	2.592	2.733	3.117	2.958	2.992	1.467	2.392	2.642	2.308
	Peak Freq Gain		25.0	(--)	0.027	0.024	0.018	0.017	0.018	0.027	0.021	0.023	0.017	0.020	0.021	0.025	0.024	0.028	0.037	0.025	0.020	0.018	0.024	0.027	0.019
	Freq @ 180 Phase Shift		25.0	(Hz)	6.133	6.692	6.592	6.800	6.617	6.417	6.442	6.500	6.558	6.442	6.618	6.350	6.575	6.542	6.158	6.442	6.525	1.717	6.508	6.542	7.317
	180 Deg Gain		25.0	(--)	0.011	0.007	0.006	0.005	0.006	0.008	0.007	0.011	0.004	0.006	0.009	0.008	0.005	0.009	0.012	0.008	0.008	0.018	0.005	0.008	0.004
Roll Angle	Inflxn Point Occurred		25.0	(--)	1	1	0	0	1	1	1	0	0	1	1	1	0	0	0	1	1	1	0	0	0
	Inflxn Point Freq		25.0	(Hz)	1.617	1.675	0.000	0.000	1.675	1.600	1.675	0.000	0.000	1.450	1.592	1.592	0.000	0.000	0.000	1.675	1.883	1.442	0.000	0.000	0.000
	Mag Gain Ratio		25.0	(--)	0.519	0.581	0.000	0.000	0.712	0.595	0.612	0.000	0.000	0.566	0.539	0.619	0.000	0.000	0.000	0.660	0.742	0.363	0.000	0.000	0.000
	Phase Angle		25.0	(deg)	48.672	65.581	0.000	0.000	73.829	59.599	52.967	0.000	0.000	76.310	69.868	66.548	0.000	0.000	0.000	74.308	79.489	65.850	0.000	0.000	0.000
Ay	1stpeak Gain Ratio		25.0	(--)	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.064	1.000	1.000	1.000	1.000
	1stpeak Frequency		25.0	(Hz)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.725	0.000	0.000	0.000	0.000
	2ndpeak Gain Ratio		25.0	(--)	3.039	1.569	1.748	1.576	1.782	2.253	1.923	2.794	1.659	1.755	2.294	2.581	1.854	2.256	3.057	2.205	2.005	1.209	1.828	1.920	1.546
	2ndpeak Frequency		25.0	(Hz)	3.950	3.850	3.850	3.950	3.950	3.650	3.650	4.042	3.417	3.658	4.042	3.650	3.383	3.725	3.650	3.725	4.042	4.617	3.200	3.508	3.233
Frequency Domain Metrics																									
Yaw Rate	Bandwidth		50.0	(Hz)	2.475	1.875	1.933	1.858	2.258	2.425	2.475	1.567	1.567	1.508	1.675	1.867	1.600	1.583	1.667	2.108	2.308	1.158	1.525	1.883	1.633
	Peak Frequency		50.0	(Hz)	0.942	0.583	0.792	0.783	0.933	0.942	0.942	0.625	0.617	0.775	0.775	0.783	0.000	0.783	0.783	0.783	0.942	0.000	0.775	0.800	0.642
	Peak Freq Gain Ratio		50.0	(--)	1.221	1.058	1.186	1.141	1.234	1.384	1.335	1.124	1.123	1.025	1.063	1.107	1.000	1.150	1.182	1.231	1.163	1.000	1.091	1.075	1.234
	Freq @ 180 Phase Shift		50.0	(Hz)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	180 Deg Gain Ratio		50.0	(--)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Load Transfer	Bandwidth		50.0	(Hz)	1.142	0.925	0.942	0.875	1.100	1.108	1.225	0.767	0.775	0.483	0.875	0.983	0.767	0.783	0.825	0.958	1.167	0.583	0.758	0.883	0.833
	Peak Frequency		50.0	(Hz)	0.592	0.000	0.000	0.000	0.592	0.592	0.608	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	Peak Freq Gain Ratio		50.0	(--)	1.031	1.000	1.000	1.000	1.011	1.064	1.068	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
	Freq @ 180 Phase Shift		50.0	(Hz)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	180 Deg Gain Ratio		50.0	(--)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Ay	Bandwidth		50.0	(Hz)	0.775	0.700	0.600	0.767	0.875	0.792	0.883	0.642	0.675	0.483	0.675	0.708	0.625	0.617	0.667	0.758	0.925	0.492	0.617	0.700	0.683
	Peak Frequency		50.0	(Hz)	4.692	0.000	0.000	0.000	0.000	4.667	0.000	4.667	0.000	0.000	0.000	4.667	0.000	4.650	4.633	4.667	0.000	0.000	0.000	0.000	0.000
	Peak Freq Gain Ratio		50.0	(--)	1.276	1.000	1.000	1.000	1.000	1.229	1.000	1.317	1.000	1.000	1.000	1.073	1.000	1.156	1.438	1.043	1.000	1.000	1.000	1.000	1.000
	Freq @ 180 Phase Shift		50.0	(Hz)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	180 Deg Gain Ratio		50.0	(--)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Roll Angle	Bandwidth		50.0	(Hz)	1.142	0.875	0.925	0.867	1.083	1.100	1.183	0.758	0.775	0.483	0.858	0.992	0.783	0.750	0.825	0.967	1.133	0.592	0.750	0.892	0.817
	Peak Frequency		50.0	(Hz)	0.592	0.000	0.000	0.000	0.583	0.583	0.600	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	Peak Freq Gain Ratio		50.0	(--)	1.034	1.000	1.000	1.000	1.011	1.061	1.061	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
	Freq @ 180 Phase Shift		50.0	(Hz)	4.983	5.267	5.283	5.550	5.150	4.783	4.958	5.617	4.833	4.508	5.767	5.242	4.775	5.167	4.875	4.875	5.458	5.600	4.367	4.842	4.983
	180 Deg Gain Ratio		50.0	(--)	0.098	0.092	0.138	0.128	0.121	0.095	0.105	0.128	0.134	0.110	0.075	0.081	0.093	0.097	0.189	0.117	0.146	0.098	0.125	0.131	0.094
Side Slip	Peak Frequency		50.0	(Hz)	0.933	0.578	0.783	0.775	0.933	0.933	0.933	0.608	0.600	0.000	0.592	0.792	0.000	0.775	0.783	0.783	1.058	0.000	0.583	0.800	0.617
	Peak Freq Gain		50.0	(--)	0.028	0.037	0.026	0.027	0.025	0.033	0.030	0.029	0.026	0.036	0.031	0.028	0.034	0.035	0.034	0.032	0.021	0.057	0.030	0.031	0.031
	Freq @ 180 Phase Shift		50.0	(Hz)	1.683	1.750	1.617	1.733	1.742	1.608	1.800	1.517	1.457	1.333	1.808	1.750	1.608	1.363	1.525	1.625	1.800	1.625	1.367	1.550	1.433
	180 Deg Gain		50.0	(--)	0.020	0.021	0.016	0.015	0.016	0.023	0.018	0.016	0.015	0.018	0.017	0.018	0.019	0.023	0.021	0.020	0.016	0.016	0.020	0.022	0.017
Roll Angle	Inflxn Point Occurred		50.0	(--)	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1
	Inflxn Point Freq		50.0	(Hz)	1.542	1.383	1.192	1.192	1.358	1.358	1.450	1.042	1.050	1.175	1.283	1.358	1.183	1.042	0.000	1.275	1.450	1.275	1.050	1.183	1.042
	Mag Gain Ratio		50.0	(--)	0.338	0.314	0.444	0.418	0.443	0.427	0.430	0.402	0.427	0.279	0.319	0.353	0.360	0.375	0.000	0.421	0.456	0.164	0.417	0.454	0.453
	Phase Angle		50.0	(deg)	42.945	54.310	77.644	83.502	64.978	54.859	48.346	83.596	86.181	49.658	61.402	61.143	72.411	72.884	0.000	68.362	75.770	44.146	79.947	80.941	86.578
Ay	1stpeak Gain Ratio		50.0	(--)	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
	1stpeak Frequency		50.0	(Hz)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	2ndpeak Gain Ratio		50.0	(--)	1.276	0.714	0.905	0.798	0.907	1.229	0.956	1.317	0.799	0.724	0.938	1.073	0.792	1.156	1.438	1.043	0.988	0.508	0.838	0.945	0.775
	2ndpeak Frequency		50.0	(Hz)	4.692	4.717	4.667	4.667	4.667	4.667	4.667	4.667	4.642	4.667	4.692	4.667	4.650	4.650	4.633	4.667	4.667	4.900	4.650	4.650	4.667
J Turn Metrics																									
Run #1																									
Abs Ay=0 5	Sideslip	Max Angle	25.0	(deg)	1.440	1.170	1.340	1.260	1.220	1.550	1.060	1.520	1.400	1.160	1.240	1.490	1.450	1.630	1.940	1.370	1.580	1.120	1.710	1.580	1.520
		Time to Ma	25.0	(sec)	0.160	0.150	0.170	0.170	0.160	0.170	0.130	0.160	0.190	0.170	0.160	0.160	0.170	0.180	0.150	0.130	0.690	0.540	0.170	0.190	0.210
		Settle Time	25.0	(sec)	1.600	1.160	1.160	1.120	1.240	1.720	1.840	1.320	1.240	1.280	1.320	1.320	1.200	1.360	1.120	1.460	1.240	1.320	1.240	1.240	1.320
	Yaw Rate	%Overshoot	25.0	(%)	6.696	7.386	4.635	4.513	4.282	4.869	6.758	2.336	3.170	6.415	4.662	4.500	4.754	3.609	1.342	5.552	4.622	6.042	3.614	2.480	3.014
		Peak Resp	25.0	(sec)	0.281	0.314	0.367	0.365	0.363	0.329	0.326	0.442	0.432	0.372	0.362	0.359	0.373	0.421	0.429	0.331	0.328	0.384	0.413	0.427	0.445
	Load Trans	Maximum	25.0	(%)	61.550	49.360	39.640	40.190	44.710	46.560	50.350	46.980	39.780	46.260	54.040	55.600	44.820	43.530	43.780	49.090	41.290	41.680	37.770	44.630	39.720
Run #2																									
% Max Ay=75	Sideslip	Max Angle	25.0	(deg)	1.460	1.210	1.440	1.360	1.300	1.540	1.070	1.570	1.460	1.230	1.260	1.500	1.520	1.940	2.000	1.430	1.740	1.240	1.820	1.640	1.610
		Time to Ma	25.0	(sec)	0.150	0.150	0.190	0.190	0.180	0.170	0.160	0.190	0.210	0.150	0.150	0.150	0.160	0.170	0.140	0.160	0.750	0.580	0.200	0.180	0.190
		Settle Time	25.0	(sec)	1.640	1.200	1.240	1.200	1.360	1.720	1.680	1.080	1.080	1.400	1.380	1.360	1.280	1.440	0.920	1.560	1.120	1.360	1.040	1.280	1.120
	Yaw Rate	%Overshoot	25.0	(%)	5.716	6.630	3.385	3.097	2.222	5.010	6.098	1.688	2.416	6.636	3.885	3.249	3.583	2.911	1.061	4.617	2.077	6.051	2.629	1.888	2.575
		Peak Resp	25.0	(sec)	0.315	0.347	0.386	0.386	0.418	0.331	0.319	0.469	0.452	0.394	0.353	0.348	0.396	0.446	0.422	0.318	0.348	0.377	0.438	0.459	0.471
	Load Trans	Maximum	25.0	(%)	63.820	52.050	45.760	45.680	51.730	46.190	52.210	53.760	44.910	54.730	56.860	59.150	50.410	46.190	46.270	53.050	46.960	44.210	42.000	47.210	43.810
Run #3																									
% Max Ay=85	Sideslip	Max Angle	25.0	(deg)	1.480	1.250	1.520	1.430	1.340	1.600	1.080	1.640	1.560	1.250	1.270	1.520	1.570	2.040	2.090	1.450	1.800	1.580	1.900	1.700	1.690
		Time to Ma	25.0	(sec)	0.130	0.130	0.200	0.200	0.190	0.150	0.140	0.170	0.230	0.130	0.130	0.170	0.170	0.190	0.160	0.130	0.810	0.600	0.220	0.160	0.210

Summary of Simulated Vehicle Metrics

Chart 2-31.
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Vehicle Description																									
Vehicle Number					262	263	267	268	257	266	289	271	239	284	273	250	145	272	274	281	285	270	122	119	275
Model Year					1977	1982	1984	1984	1982	1983	1980	1983	1983	1987	1982	1987	1983	1985	1985	1989	1980	1984	1985	1987	1980
Make					Renault	Toyota	Honda	Honda	Honda	Nissan	Chevrolet	olkswage	Dodge	Datsun	B.M.W	Hyundai	Toyota	Nissan	Chevrolet	Ford	Datsun	Pontiac	Oldsmobil	Ford	Buick
Model					LeCar	Starlet	CRX	Civic HB	Civic 4dr	Sentra	Chevette	Jetta	Omni	510	320i	Excel	Camry	Stanza4dr	Cavalier	Escort	200SX	Fiero	Ciera	T'bird	LeSabre
Parameter Source					STI	STI	STI	STI	STI	STI	STI	STI	CPMD	STI	STI	CPMD	CPMD	STI	STI	STI	STI	STI	CPMD	CPMD	STI
Vehicle Configuration																									
		Settle Time	25.0	(sec)	1.720	1.280	1.360	1.320	1.160	1.880	1.560	1.240	1.200	1.560	1.460	1.440	1.360	1.600	0.960	1.640	1.160	1.560	1.160	1.120	1.320
	Yaw Rate	%Overshoot	25.0	(%)	3.214	5.465	2.183	1.923	1.455	3.607	4.599	1.013	1.939	6.766	2.331	1.377	2.431	2.493	0.584	2.982	0.221	6.738	2.061	1.121	2.416
		Peak Resp	25.0	(sec)	0.333	0.331	0.444	0.444	0.474	0.349	0.377	0.530	0.509	0.410	0.412	0.407	0.414	0.470	0.524	0.334	1.048	0.399	0.498	0.521	0.527
	Load Trans	Maximum	25.0	(%)	69.730	57.670	50.970	50.990	57.510	53.070	56.990	60.120	50.450	61.760	62.680	65.180	56.260	53.510	51.980	58.920	51.680	49.680	46.960	53.000	49.490
Run #4																									
% Max Ay=95	Sideslip	Max Angle	25.0	(deg)	1.480	1.270	1.570	1.490	1.360	1.610	1.080	1.710	1.630	1.250	1.270	1.530	1.580	2.100	2.130	1.450	1.630	2.100	1.960	1.740	1.720
		Time to Ma	25.0	(sec)	0.100	0.150	0.210	0.210	0.200	0.120	0.110	0.230	0.240	0.100	0.150	0.140	0.140	0.210	0.140	0.100	0.260	0.700	0.190	0.180	0.220
		Settle Time	25.0	(sec)	2.260	1.520	1.600	1.200	1.520	2.160	2.080	1.040	1.480	1.960	1.320	1.560	1.480	1.960	1.200	1.760	0.720	1.920	1.400	1.560	2.080
	Yaw Rate	%Overshoot	25.0	(%)	2.301	4.712	1.773	1.565	2.488	2.962	4.165	2.872	2.388	6.918	1.526	0.551	1.456	3.085	0.856	1.365	0.021	8.445	2.115	1.752	3.258
		Peak Resp	25.0	(sec)	1.143	0.389	0.494	0.494	0.559	0.396	0.426	0.627	0.598	0.458	0.466	1.258	0.463	0.525	0.620	1.099	0.942	0.456	0.591	0.656	0.696
	Load Trans	Maximum	25.0	(%)	75.350	83.020	56.320	56.470	64.150	58.050	62.330	67.780	56.180	66.990	66.160	71.010	62.080	58.770	57.720	64.640	55.960	55.300	51.950	59.510	55.780
J Turn Metrics																									
Run #5																									
Abs Ay=0.4	Sideslip	Max Angle	50.0	(deg)	1.190	1.280	1.180	1.230	1.150	1.430	1.390	1.390	1.330	1.640	1.310	1.130	1.420	1.410	1.260	1.410	0.790	2.120	1.370	1.100	1.580
		Time to Ma	50.0	(sec)	0.640	0.770	0.720	0.760	0.680	0.640	0.640	0.880	0.840	1.040	0.810	0.730	0.850	0.890	0.770	0.720	0.600	1.250	0.930	0.810	0.880
		Settle Time	50.0	(sec)	1.040	1.080	1.120	1.120	1.120	1.600	1.120	1.360	1.320	1.400	1.160	1.120	1.240	1.360	1.280	1.120	0.920	1.080	1.360	1.240	1.400
	Yaw Rate	%Overshoot	50.0	(%)	14.289	9.103	12.407	11.252	13.709	25.416	20.109	9.926	10.472	8.397	8.327	9.740	9.546	11.989	14.840	17.953	10.239	4.236	9.566	9.723	15.847
		Peak Resp	50.0	(sec)	0.322	0.415	0.402	0.445	0.361	0.320	0.362	0.521	0.520	0.564	0.447	0.405	0.489	0.467	0.488	0.403	0.364	0.694	0.525	0.491	0.479
	Load Trans	Maximum	50.0	(%)	45.230	37.570	31.670	31.940	35.490	38.860	39.460	39.480	32.190	37.430	40.990	41.920	35.160	34.970	36.030	38.490	31.620	33.090	30.570	36.160	32.710
Run #6																									
% Max Ay=75	Sideslip	Max Angle	50.0	(deg)	1.790	1.990	1.980	2.020	2.200	2.090	2.470	2.210	2.160	3.110	2.070	1.750	2.280	2.230	1.880	2.220	1.410	3.140	2.190	1.940	2.560
		Time to Ma	50.0	(sec)	0.630	0.720	0.740	0.750	0.780	0.670	0.700	0.990	0.860	0.870	0.790	0.750	0.790	0.910	0.600	0.660	0.670	1.120	0.910	0.880	0.900
		Settle Time	50.0	(sec)	1.520	1.240	1.280	1.320	1.920	1.800	1.960	1.680	1.520	2.040	1.400	1.280	1.360	1.560	1.640	1.640	1.160	1.760	1.560	1.560	2.240
	Yaw Rate	%Overshoot	50.0	(%)	21.800	17.850	18.599	17.347	20.587	33.498	30.105	12.908	15.664	24.968	14.815	14.913	16.532	17.377	21.189	29.800	14.754	11.837	15.867	17.202	22.938
		Peak Resp	50.0	(sec)	0.348	0.404	0.424	0.427	0.380	0.346	0.344	0.506	0.501	0.465	0.433	0.390	0.433	0.473	0.435	0.345	0.345	0.604	0.510	0.477	0.502
	Load Trans	Maximum	50.0	(%)	59.360	51.880	46.540	46.360	52.490	47.520	54.000	54.720	46.020	56.520	56.440	56.690	50.750	48.130	48.010	53.170	46.830	44.940	42.960	50.780	45.590
Run #7																									
% Max Ay=85	Sideslip	Max Angle	50.0	(deg)	2.350	2.610	2.520	2.560	2.950	2.820	3.590	2.850	2.730	4.100	2.730	2.250	2.880	2.850	2.370	2.820	1.880	3.930	2.780	2.680	3.450
		Time to Ma	50.0	(sec)	0.620	0.720	0.730	0.760	0.810	0.690	0.810	1.060	0.890	0.850	0.880	0.740	0.780	0.900	0.790	0.650	0.690	1.040	0.900	0.910	0.970
		Settle Time	50.0	(sec)	2.120	1.880	1.880	1.920	2.160	2.560	3.080	1.920	2.240	2.240	2.240	1.920	1.960	2.320	1.960	2.160	1.760	1.840	2.280	2.480	2.600
	Yaw Rate	%Overshoot	50.0	(%)	30.467	26.566	24.792	23.530	27.106	42.609	39.053	15.980	21.073	36.715	20.999	20.820	26.540	23.391	27.497	39.952	19.301	19.923	22.325	23.899	30.113
		Peak Resp	50.0	(sec)	0.337	0.395	0.412	0.416	0.408	0.333	0.370	0.537	0.489	0.452	0.422	0.380	0.421	0.464	0.425	0.330	0.375	0.556	0.500	0.467	0.489
	Load Trans	Maximum	50.0	(%)	67.570	59.720	53.190	53.030	59.860	53.670	61.910	62.280	52.570	66.230	64.760	64.760	58.440	54.530	54.740	60.800	53.360	51.470	49.020	58.430	52.450
Run #8																									
% Max Ay=95	Sideslip	Max Angle	50.0	(deg)	3.440	3.920	3.430	3.480	4.210	3.990	24.780	3.760	3.700	24.750	4.440	3.120	3.760	3.910	3.100	3.660	2.660	5.410	3.800	4.380	5.700
		Time to Ma	50.0	(sec)	0.640	0.760	0.710	0.760	0.790	0.710	-	1.000	0.870	-	1.250	0.760	0.760	0.890	0.770	0.620	0.720	1.020	0.880	1.090	1.470
		Settle Time	50.0	(sec)	2.880	3.400	2.560	2.600	3.560	3.360	-	2.660	3.040	-	3.600	2.660	2.560	3.120	2.640	3.160	2.520	3.520	3.120	4.000	99.990
	Yaw Rate	%Overshoot	50.0	(%)	47.279	42.059	37.345	36.001	40.478	56.503	-	24.173	32.334	-	30.305	32.333	39.601	35.888	37.488	53.647	29.352	36.264	34.625	33.946	38.381
		Peak Resp	50.0	(sec)	0.317	0.380	0.392	0.396	0.385	0.347	-	0.525	0.469	-	0.408	0.363	0.402	0.448	0.409	0.305	0.358	0.502	0.442	0.448	0.472
	Load Trans	Maximum	50.0	(%)	75.930	66.080	60.030	59.950	67.300	59.590	66.070	70.070	59.320	75.900	74.050	73.270	66.470	60.960	61.720	66.230	60.320	58.830	55.230	66.480	60.220
Single sine metrics																									
Run #1																									
Abs Freq=.5 Amp=85%	Sideslip	Max Angle	25.0	(deg)	1.260	0.920	1.330	1.270	1.220	1.310	0.930	1.410	1.420	1.190	1.100	1.350	1.340	1.670	1.740	1.250	1.820	1.660	1.640	1.410	1.490
		Time to Ma	25.0	(sec)	0.280	0.280	0.380	0.400	0.320	0.280	0.240	0.400	0.360	1.120	0.280	0.280	0.320	0.380	0.520	0.280	1.600	0.920	0.360	0.360	0.360
		Settle Time	25.0	(sec)	1.000	0.760	0.840	0.800	0.880	1.000	1.200	0.960	0.840	0.720	0.960	0.960	0.640	0.760	0.640	0.920	0.760	0.660	0.660	0.660	0.960
	Yaw Rate	Max/SS	25.0	(-)	0.973	1.001	1.000	0.999	0.996	0.988	1.001	0.988	1.005	1.035	0.994	0.985	0.999	0.999	0.990	0.989	0.993	1.030	1.000	0.989	1.003
		Peak Resp	25.0	(sec)	0.973	0.990	0.991	0.992	0.981	0.956	0.966	0.986	0.988	0.976	0.977	0.976	0.984	0.979	0.990	0.976	1.009	0.985	0.987	0.984	0.984
	Load Trans	Maximum	25.0	(%)	67.860	55.160	49.640	49.620	56.110	52.470	55.470	57.560	48.150	59.360	60.790	63.750	55.250	52.110	50.960	57.680	50.670	46.550	45.170	50.480	46.830
Run #2																									
Abs Freq=.5 Amp=95%	Sideslip	Max Angle	25.0	(deg)	1.470	1.070	1.500	1.420	1.380	1.530	1.080	1.570	1.590	1.670	1.240	1.540	1.540	1.890	1.920	1.470	1.980	2.200	1.640	1.570	1.680
		Time to Ma	25.0	(sec)	0.240	0.280	0.320	0.380	0.280	0.280	0.240	0.360	0.380	1.120	0.280	0.280	0.280	0.320	0.520	0.280	1.600	0.960	0.360	0.320	0.320
		Settle Time	25.0	(sec)	1.040	0.600	0.880	0.640	0.920	1.040	1.240	1.040	0.920	0.780	1.000	1.000	0.920	1.040	0.920	0.960	0.780	0.720	0.760	0.920	1.000
	Yaw Rate	Max/SS	25.0	(-)	0.960	1.006	1.007	1.003	1.013	1.001	1.021	1.001	1.009	1.054	0.998	0.985	1.002	1.009	0.990	0.993	0.990	1.052	1.002	0.993	1.008
		Peak Resp	25.0	(sec)	0.934	0.976	0.980	0.986	0.960	0.924	0.937	0.982	0.981	0.974	0.964	0.958	0.972	0.971	0.988	0.955	1.005	0.979	0.982	0.975	0.981
	Load Trans	Maximum	25.0	(%)	74.580	61.190	55.290	55.200	63.140	59.140	62.230	64.000	53.520	67.250	66.960	70.620	61.760	57.940	56.690	64.570	55.500	52.480	50.380	56.540	52.440
Run #3																									
Abs Freq=1 Amp=85%	Sideslip	Max Angle	25.0	(deg)	1.860	1.410	1.750	1.630	1.740	2.300	2.040	2.180	2.000	2.540	1.770	2.040	2.010	2.620	2.200	1.900	1.840	2.460	2.360	1.920	2.130
		Time to Ma	25.0	(sec)	0.200	0.640	0.240	0.240	0.640	0.640	1.040	0.680	0.680	0.640	0.640	0.640	0.680	0.680	0.240	0.640	0.240	1.040	0.680	0.680	0.680
		Settle Time	25.0	(sec)	1.160	0.880	0.920	0.880	1.240	1.160	1.360	1.080	1.000	0.800	1.080	1.120	1.000	1.120	0.960	1.040	0.840	0.600	1.000	0.960	1.080
	Yaw Rate	Max/SS	25.0	(-)	1.080	1.062	1.036	1.016	1.043	1.103	1.134	0.975	0.998	1.137	1.045	1.031	1.036	1.010	0.959	1.069	0.987	1.090	0.997	0.979	1.001
		Peak Resp	25.0	(sec)	1.011	1.033	1.040	1.033	1.052	1.070	1.083	1.046	1.052	1.086	1.046	1.034	1.042	1.056	1.020	1.034	0.987	1.076	1.055	1.048	1.059
	Load Trans	Maximum	25.0	(%)	77.400	57.970	50.510	50.530	60.460	55.930	62.280	51.920	44.400	54.350	62.720	67.750	56.000	46.620	50.690	61.310	56.100	39.150	41.660	46.520	42.560
Run #4																									
% Peak Freq=100 Amp=85%	Sideslip	Max Angle	25.0	(deg)	3.280	2.130	2.340	2.050	2.460	3.090	2.520	0.000	1.800	0.000	2.370	2.930	2.520	2.640	0.000	2.800	2.250	2.350	1.940	2.250	0.000
		Time to Ma	25.0	(sec)	0.440	0.460	0.520	0.520	0.480	0.520	0.480	0.000	0.760	0.000	0.520	0.480	0.560	0.680	0.000	0.480	0.440	1.160	0.280	0.560	0.000
		Settle Time	25.0	(sec)	1.240	0.920	0.960	0.920	1.240	1.200	1.400	0.000	0.960	0.000	1.120	1.160	1.000	1.120	0.000	1.040	0.920	0.720	0.720	1.000	0.000
	Yaw Rate	Max/SS	25.0	(-)	1.211	1.088	1.022	1.005	1.025	1.154	1.167	0.000	1.002	0.000	1.064	1.055	1.041	1.012	0.000	1.121	1.012	1.077	0.995	0.945	0.000
		Peak Resp	25.0	(sec)	1.211	1.150	1.119	1.114	1.140	1.186	1.194	0.000	1.031	0.000	1.118	1.144	1.105	1.060	0.000	1.147	1.132	1.050	1.012	1.068	0.000
	Load Trans	Maximum	25.0	(%)	52.640	41.850	42.520	43.340	49.250	43.880	45.170	0.000	47.380	0.000	47.820	51.900	49.220	46.120	0.000	50.910	44.260	42.910	46.260	42.140	0.000

Single sine metrics

Chart 2-31.
Page 4.

Vehicle Description																									
Vehicle Number					282	263	267	268	257	266	269	271	239	264	273	250	145	272	274	281	265	270	122	119	275
Model Year					1977	1982	1984	1984	1982	1983	1980	1983	1983	1987	1982	1987	1983	1985	1985	1989	1980	1984	1985	1987	1980
Make					Renault	Toyota	Honda	Honda	Honda	Nissan	Chevrolet	olkswage	Dodge	Datsun	B.M.W	Hyundai	Toyota	Nissan	Chevrolet	Ford	Datsun	Pontiac	Oldsmobil	Ford	Buick
Model			-	-	LeCar	Starlet	CRX	Civic HB	Civic 4dr	Sentra	Chevette	Jetta	Omni	510	320I	Excel	Camry	Stanza4dr	Cavalier	Escort	200SX	Fiero	Clera	T'bird	LeSabre
Parameter Source					STI	STI	STI	STI	STI	STI	STI	STI	CPMD	STI	STI	CPMD	CPMD	STI	STI	STI	STI	STI	CPMD	CPMD	STI
Vehicle Configuration																									
Run#5																									
Abs Freq= 5	Sideslip	Max Angle	50.0	(deg)	2 250	2.500	2.500	2 510	2.840	2.880	3.610	2.690	2.690	4.060	2.580	2.220	2.840	2.870	2.460	2.820	1.780	3.350	2.790	2.670	3 350
Amp=85%		Time to Ma	50 0	(sec)	1.800	1.880	1.880	1.880	1.880	1.840	1.880	1.960	1.960	2.000	1.880	1.880	1.920	1.960	1.920	1.800	1.880	0.960	2.000	1.960	1.960
		Settle Time	50.0	(sec)	0 880	0.600	0.920	0 920	0.920	0.960	1.240	1.120	1.040	0.880	0.960	0.920	0.680	1.160	1.040	0 920	0.720	1.040	0.760	0.960	1.200
	Yaw Rate	Max/SS	50 0	(--)	1 232	1 248	1 236	1 224	1.282	1.418	1.434	1.168	1.229	1.415	1.196	1.161	1 279	1.258	1.298	1 385	1.137	1.172	1.249	1 282	1.358
		Peak Resp	50 0	(sec)	1 014	1 041	1 044	1 041	1.069	1 083	1.117	1.057	1.065	1.089	1.042	1.029	1.062	1.076	1.069	1 058	1.007	1.041	1.071	1.091	1.101
	Load Trans	Maximum	50.0	(%)	65 930	56 730	50 490	49 430	57.220	53 960	60.150	54.890	47.880	61.900	59.880	61.640	54.410	50.270	50.690	59.200	50.500	44.010	45.030	54 250	48 150
Run #6																									
Abs Freq= 5	Sideslip	Max Angle	50.0	(deg)	3 380	3.890	3.530	3 510	4.600	4.560	24.750	3.630	3 810	6.610	3.800	3.170	3.660	4.130	3.340	3.800	2.550	4.810	4.000	4.740	4 880
Amp=95%		Time to Ma	50.0	(sec)	1.760	1.920	1.880	1.880	1 880	1.800	-	2.000	1.960	2.080	1.920	1.840	1.880	2.000	1.920	1.760	1.840	2.040	2.000	2.040	2.000
		Settle Time	50.0	(sec)	0.920	0.960	0.960	0.960	1.000	1.360	-	1.200	1.160	1.000	1.080	1.000	1.000	1.280	1.080	0.920	0.800	1.160	1 200	1.200	1.320
	Yaw Rate	Max/SS	50.0	(--)	1.413	1.456	1.407	1.389	1.525	1.713	-	1.280	1.403	1.685	1.331	1.338	1.458	1.447	1.458	1.561	1.251	1.415	1.441	1.537	1.513
		Peak Resp	50 0	(sec)	1.051	1.100	1.083	1 079	1.150	1.187	-	1.088	1.106	1.178	1.087	1.071	1.102	1.123	1.110	1.093	1.032	1.092	1.124	1.200	1.161
	Load Trans	Maximum	50.0	(%)	76 630	66.140	58.640	57.850	66.230	63.140	71.240	62.690	58.070	71.730	69.040	72.540	64.110	58.840	58.910	67.850	58.030	52.590	52.770	63.470	54.620
Run #7																									
Abs Freq=1.	Sideslip	Max Angle	50.0	(deg)	2.360	2.090	2.130	2 040	2.500	2.820	3.110	2.050	2.060	3.070	2.050	1.970	2.320	2.300	2.170	2.690	1.660	2.360	2.210	2 100	2.370
Amp=85%		Time to Ma	50.0	(sec)	1.080	0.600	0.600	0.600	1.080	1.080	1.080	0.640	0.600	0.640	0.600	0.600	0.600	0.640	0.640	1.080	1.040	0.600	0.640	0 640	0.640
		Settle Time	50.0	(sec)	1.000	0.880	1.000	1.000	1.040	1.120	1.320	1.160	0.760	1.000	1.040	1.000	0.800	1.240	1.160	1.080	0.840	1.080	0.840	1.000	1.280
	Yaw Rate	Max/SS	50.0	(--)	1.434	1.259	1.304	1.253	1.408	1.703	1.642	1.078	1.150	1.298	1.165	1.219	1.225	1.168	1.289	1.578	1.273	1.006	1.153	1.254	1.270
		Peak Resp	50.0	(sec)	1.145	1.070	1.133	1.121	1.187	1.258	1.248	1.082	1.087	1.030	1.080	1.112	1.071	1.083	1.123	1.183	1.131	0.941	1.076	1.120	1.124
	Load Trans	Maximum	50.0	(%)	56.850	43.630	37.630	36.300	45.200	44.740	51.950	37.440	33.750	43.910	43.350	45.880	39.960	35.000	40.350	48.170	42.900	28.170	32.140	40.790	33.090
Run #8																									
% Peak Freq=100	Sideslip	Max Angle	50.0	(deg)	2.480	2.530	2.480	2.390	2.640	2.950	3.250	2.570	2.640	3.470	2.380	2.280	-	2.480	2.430	3.110	1.880	-	2.450	2.370	3.210
Amp=85%		Time to Ma	50.0	(sec)	1.120	1.680	1.320	1.320	1.120	1.160	1.120	1.640	1.640	0.760	1.320	1.320	-	1.360	1.320	1.320	1.120	-	1.440	1.320	1.600
		Settle Time	50.0	(sec)	0.960	0.600	1.000	0.960	1.000	1.120	1.320	1.160	1.080	1.000	1.040	1.000	-	1.240	1.120	1.040	0.800	-	0.800	1.040	1.240
	Yaw Rate	Max/SS	50.0	(--)	1.412	1.278	1.334	1.298	1.408	1.697	1.637	1.166	1.260	1.425	1.236	1.259	-	1.278	1.385	1.576	1.262	-	1.264	1.327	1.408
		Peak Resp	50.0	(sec)	1.112	1.066	1.121	1.114	1.170	1.237	1.227	1.089	1.097	1.062	1.090	1.103	-	1.119	1.150	1.167	1.101	-	1.101	1.141	1.141
	Load Trans	Maximum	50.0	(%)	59.310	55.760	44.150	42.100	47.220	46.740	54.510	49.870	44.630	52.030	51.240	54.930	-	40.040	42.540	55.530	44.440	-	37.480	45.670	44.610

From Ford Provided Data

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Number of Vehicle in Sample	27
Average Production Year	1995

Average Wheelbase	103.0704	Std. Deviation Wheelbase	6.13
Average Curb Weight	2773	Std. Deviation Curb Weight	472
Average Test Weight	3163	Std. Deviation Test Weight	492
Average Steering Ratio	17.3	Std. Deviation Steering Ratio	1.62
Avg. Off Center Yaw Gain @ 30 Mph	-	Std. Deviation Off Center Yaw Gain @ 30 Mph	-
Avg. Steering Torque Gradient @ 30 Mph	156.5	Std. Deviation Steering Torque Gradient @ 30 Mph	32.64
Avg. Torsional Rate @ 30 Mph	0.898	Std. Deviation Torsional Rate @ 30 Mph	0.197
Avg. Off Center Yaw Gain @ 45 Mph	28.8	Std. Deviation Off Center Yaw Gain @ 45 Mph	4.43
Avg. Steering Torque Gradient @ 45 Mph	158.4	Std. Deviation Steering Torque Gradient @ 45 Mph	30.29
Avg. Torsional Rate @ 45 Mph	1.4	Std. Deviation Torsional Rate @ 45 Mph	0.283
Avg. Off Center Yaw Gain @ 60 Mph	27.9	Std. Deviation Off Center Yaw Gain @ 60 Mph	5.99
Avg. Steering Torque Gradient @ 60 Mph	164.6	Std. Deviation Steering Torque Gradient @ 60 Mph	31.84
Avg. Torsional Rate @ 60 Mph	1.9	Std. Deviation Torsional Rate @ 60 Mph	0.361
Avg. Off Center Yaw Gain @ 75 Mph	25.2	Std. Deviation Off Center Yaw Gain @ 75 Mph	6.116
Avg. Steering Torque Gradient @ 75 Mph	152.9	Std. Deviation Steering Torque Gradient @ 75 Mph	42.53
Avg. Torsional Rate @ 75 Mph	2.1	Std. Deviation Torsional Rate @ 75 Mph	0.430
Frequency Response Tests		**Frequency Response Tests**	
Ay/ Steering Wheel Angle		***Ay/ Steering Wheel Angle***	
Avg. Steering Sensitivity @ 45 Mph	0.9	Std. Deviation Steering Sensitivity @ 45 Mph	0.133
Avg. -3dB Frequency From Steering Sensitivity @ 45 Mph	1.2	Std. Deviation -3dB Frequency From Steering Sensitivity @ 45 Mph	0.168
Avg. 45 Deg Phase Lag Time @ 45 Mph	149.8	Std. Deviation 45 Deg Phase Lag Time @ 45 Mph	39.42
Avg. Steering Sensitivity @ 60 Mph	1.2	Std. Deviation Steering Sensitivity @ 60 Mph	0.188
Avg. -3dB Frequency From Steering Sensitivity @ 60 Mph	1.1	Std. Deviation -3dB Frequency From Steering Sensitivity @ 60 Mph	0.163
Avg. 45 Deg Phase Lag Time @ 60 Mph	174.0	Std. Deviation 45 Deg Phase Lag Time @ 60 Mph	27.61
Avg. Steering Sensitivity @ 75 Mph	1.3	Std. Deviation Steering Sensitivity @ 75 Mph	0.2373
Avg. -3dB Frequency From Steering Sensitivity @ 75 Mph	1.1	Std. Deviation -3dB Frequency From Steering Sensitivity @ 75 Mph	0.1660
Avg. 45 Deg Phase Lag Time @ 75 Mph	175.0	Std. Deviation 45 Deg Phase Lag Time @ 75 Mph	46.412
Yaw/ Steering Wheel Angle		***Yaw/ Steering Wheel Angle***	
Avg. Yaw Peak Frequency @ 45 Mph	1.2	Std. Deviation Yaw Peak Frequency @ 45 Mph	0.269
Avg. 45 Deg. Phase Lag Time @ 45 Mph	101.1	Std. Deviation 45 Deg. Phase Lag Time @ 45 Mph	13.060
Avg. Yaw Peak/Steady State Magnitude @ 45 Mph	1.2	Std. Deviation Yaw Peak/Steady State Magnitude @ 45 Mph	0.092
Avg. Yaw Peak Frequency @ 60 Mph	1.1	Std. Deviation Yaw Peak Frequency @ 60 Mph	0.180
Avg. 45 Deg. Phase Lag Time @ 60 Mph	103.8	Std. Deviation 45 Deg. Phase Lag Time @ 60 Mph	12.41296
Avg. Yaw Peak/Steady State Magnitude @ 60 Mph	1.5	Std. Deviation Yaw Peak/Steady State Magnitude @ 60 Mph	0.167
Avg. Yaw Peak Frequency @ 75 Mph	1.1	Std. Deviation Yaw Peak Frequency @ 75 Mph	0.180
Avg. 45 Deg. Phase Lag Time @ 75 Mph	105.8	Std. Deviation 45 Deg. Phase Lag Time @ 75 Mph	12.570
Avg. Yaw Peak/Steady State Magnitude @ 75 Mph	1.8	Std. Deviation Yaw Peak/Steady State Magnitude @ 75 Mph	0.241
Roll /Ay		***Roll /Ay***	
Avg. Roll Peak Frequency @ 45 Mph	2.3	Std. Deviation Roll Peak Frequency @ 45 Mph	0.480
Avg. Roll Peak/Steady State Magnitude @ 45 Mph	2.0	Std. Deviation Roll Peak/Steady State Magnitude @ 45 Mph	0.638
Avg. Roll Peak Frequency @ 60 Mph	2.3	Std. Deviation Roll Peak Frequency @ 60 Mph	0.489
Avg. Roll Peak/Steady State Magnitude @ 60 Mph	2.0	Std. Deviation Roll Peak/Steady State Magnitude @ 60 Mph	0.674
Avg. Roll Peak Frequency @ 75 Mph	2.2	Std. Deviation Roll Peak Frequency @ 75 Mph	0.571
Avg. Roll Peak/Steady State Magnitude @ 75 Mph	1.8	Std. Deviation Roll Peak/Steady State Magnitude @ 75 Mph	0.730
Avg. Yaw Overshoot (.5G @ 60 Mph)	0.6	Std. Deviation Yaw Overshoot (.5G @ 60 Mph)	0.526
Avg. Yaw Overshoot (.7G @ 75 Mph)	3.3	Std. Deviation Yaw Overshoot (.7G @ 75 Mph)	1.156
Avg. Understeer Gradient (<.3 G's)	3.2	Std. Deviation Understeer Gradient (<.3 G's)	0.99
Avg. Roll Gradient	4.8	Std. Deviation Roll Gradient	1.134

Number of Vehicle in Sample	27
Average Production Year	1995

Max Wheelbase	117	Min. Wheelbase	93.50
Max Curb Weight	4065	Min. Curb Weight	2120.00
Max Test Weight	4497	Min. Test Weight	2424.00
Max Steering Ratio	23	Min. Steering Ratio	15
Max Off Center Yaw Gain @ 30 Mph	-	Min. Off Center Yaw Gain @ 30 Mph	-
Max Steering Torque Gradient @ 30 Mph	232	Min. Steering Torque Gradient @ 30 Mph	87.00
Max Torsional Rate @ 30 Mph	1.44	Min. Torsional Rate @ 30 Mph	0.58
Max Off Center Yaw Gain @ 45 Mph	33.9	Min. Off Center Yaw Gain @ 45 Mph	25.90
Max Steering Torque Gradient @ 45 Mph	243	Min. Steering Torque Gradient @ 45 Mph	96.00
Max Torsional Rate @ 45 Mph	2.05	Min. Torsional Rate @ 45 Mph	0.97
Max Off Center Yaw Gain @ 60 Mph	34.8	Min. Off Center Yaw Gain @ 60 Mph	23.80
Max Steering Torque Gradient @ 60 Mph	239	Min. Steering Torque Gradient @ 60 Mph	99.00
Max Torsional Rate @ 60 Mph	2.63	Min. Torsional Rate @ 60 Mph	1.27
Max Off Center Yaw Gain @ 75 Mph	32.2	Min. Off Center Yaw Gain @ 75 Mph	21.10
Max Steering Torque Gradient @ 75 Mph	205	Min. Steering Torque Gradient @ 75 Mph	2.23
Max Torsional Rate @ 75 Mph	2.85	Min. Torsional Rate @ 75 Mph	1.40
Frequency Response Tests		**Frequency Response Tests**	
Ay/ Steering Wheel Angle		***Ay/ Steering Wheel Angle***	
Max Steering Sensitivity @ 45 Mph	1.2	Min. Steering Sensitivity @ 45 Mph	0.61
Max -3dB Frequency From Steering Sensitivity @ 45 Mph	1.56	Min. -3dB Frequency From Steering Sensitivity @ 45 Mph	0.90
Max 45 Deg Phase Lag Time @ 45 Mph	218	Min. 45 Deg Phase Lag Time @ 45 Mph	0.15
Max Steering Sensitivity @ 60 Mph	1.6	Min. Steering Sensitivity @ 60 Mph	0.75
Max -3dB Frequency From Steering Sensitivity @ 60 Mph	1.55	Min. -3dB Frequency From Steering Sensitivity @ 60 Mph	0.88
Max 45 Deg Phase Lag Time @ 60 Mph	231	Min. 45 Deg Phase Lag Time @ 60 Mph	126.00
Max Steering Sensitivity @ 75 Mph	1.9	Min. Steering Sensitivity @ 75 Mph	0.78
Max -3dB Frequency From Steering Sensitivity @ 75 Mph	1.55	Min. -3dB Frequency From Steering Sensitivity @ 75 Mph	0.83
Max 45 Deg Phase Lag Time @ 75 Mph	245	Min. 45 Deg Phase Lag Time @ 75 Mph	0.20
Yaw/ Steering Wheel Angle		***Yaw/ Steering Wheel Angle***	
Max Yaw Peak Frequency @ 45 Mph	1.71	Min. Yaw Peak Frequency @ 45 Mph	0.73
Max 45 Deg. Phase Lag Time @ 45 Mph	136	Min. 45 Deg. Phase Lag Time @ 45 Mph	82.00
Max Yaw Peak/Steady State Magnitude @ 45 Mph	1.4	Min. Yaw Peak/Steady State Magnitude @ 45 Mph	1.04
Max Yaw Peak Frequency @ 60 Mph	1.51	Min. Yaw Peak Frequency @ 60 Mph	0.83
Max 45 Deg. Phase Lag Time @ 60 Mph	135	Min. 45 Deg. Phase Lag Time @ 60 Mph	84.00
Max Yaw Peak/Steady State Magnitude @ 60 Mph	1.85	Min. Yaw Peak/Steady State Magnitude @ 60 Mph	1.18
Max Yaw Peak Frequency @ 75 Mph	1.46	Min. Yaw Peak Frequency @ 75 Mph	0.68
Max 45 Deg. Phase Lag Time @ 75 Mph	138	Min. 45 Deg. Phase Lag Time @ 75 Mph	85.00
Max Yaw Peak/Steady State Magnitude @ 75 Mph	2.27	Min. Yaw Peak/Steady State Magnitude @ 75 Mph	1.33
Roll /Ay		***Roll /Ay***	
Max Roll Peak Frequency @ 45 Mph	2.69	Min. Roll Peak Frequency @ 45 Mph	0.15
Max Roll Peak/Steady State Magnitude @ 45 Mph	2.52	Min. Roll Peak/Steady State Magnitude @ 45 Mph	1.29
Max Roll Peak Frequency @ 60 Mph	2.69	Min. Roll Peak Frequency @ 60 Mph	0.10
Max Roll Peak/Steady State Magnitude @ 60 Mph	2.61	Min. Roll Peak/Steady State Magnitude @ 60 Mph	1.27
Max Roll Peak Frequency @ 75 Mph	2.73	Min. Roll Peak Frequency @ 75 Mph	0.10
Max Roll Peak/Steady State Magnitude @ 75 Mph	2.41	Min. Roll Peak/Steady State Magnitude @ 75 Mph	1.00
Max Yaw Overshoot (.5G @ 60 Mph)	2.2	Min. Yaw Overshoot (.5G @ 60 Mph)	0.03
Max Yaw Overshoot (.7G @ 75 Mph)	5.45	Min. Yaw Overshoot (.7G @ 75 Mph)	2.08
Max Understeer Gradient (<.3 G's)	6.5	Min. Understeer Gradient (<.3 G's)	1.80
Max Roll Gradient	7.4	Min. Roll Gradient	2.70

From Ford Provided Data

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Number of Vehicle in Sample	27
Average Production Year	1995

Max +25% Wheelbase	146.25	Min. -25% Wheelbase	70.13
Max +25% Curb Weight	5081	Min. -25% Curb Weight	1590.00
Max +25% Test Weight	5621	Min. -25% Test Weight	1818.00
Max +25% Steering Ratio	29	Min. -25% Steering Ratio	11
Max +25% Off Center Yaw Gain @ 30 Mph	-	Min. -25% Off Center Yaw Gain @ 30 Mph	-
Max +25% Steering Torque Gradient @ 30 Mph	290	Min. -25% Steering Torque Gradient @ 30 Mph	65.25
Max +25% Torsional Rate @ 30 Mph	1.8	Min. -25% Torsional Rate @ 30 Mph	0.44
Max +25% Off Center Yaw Gain @ 45 Mph	42.375	Min. -25% Off Center Yaw Gain @ 45 Mph	19.43
Max +25% Steering Torque Gradient @ 45 Mph	303.75	Min. -25% Steering Torque Gradient @ 45 Mph	72.00
Max +25% Torsional Rate @ 45 Mph	2.563	Min. -25% Torsional Rate @ 45 Mph	0.73
Max +25% Off Center Yaw Gain @ 60 Mph	43.5	Min. -25% Off Center Yaw Gain @ 60 Mph	17.85
Max +25% Steering Torque Gradient @ 60 Mph	298.75	Min. -25% Steering Torque Gradient @ 60 Mph	74.25
Max +25% Torsional Rate @ 60 Mph	3.2875	Min. -25% Torsional Rate @ 60 Mph	0.95
Max +25% Off Center Yaw Gain @ 75 Mph	40.25	Min. -25% Off Center Yaw Gain @ 75 Mph	15.83
Max +25% Steering Torque Gradient @ 75 Mph	256.25	Min. -25% Steering Torque Gradient @ 75 Mph	1.67
Max +25% Torsional Rate @ 75 Mph	3.563	Min. -25% Torsional Rate @ 75 Mph	1.05
Frequency Response Tests		**Frequency Response Tests**	
Ay/ Steering Wheel Angle		***Ay/ Steering Wheel Angle***	
Max +25% Steering Sensitivity @ 45 Mph	1.5	Min. -25% Steering Sensitivity @ 45 Mph	0.46
Max +25% -3dB Freq. From Steering Sensitivity @ 45 Mph	1.95	Min. -25% -3dB Frequency From Steering Sensitivity @ 45 Mph	0.68
Max +25% 45 Deg Phase Lag Time @ 45 Mph	272.5	Min. -25% 45 Deg Phase Lag Time @ 45 Mph	0.11
Max +25% Steering Sensitivity @ 60 Mph	2	Min. -25% Steering Sensitivity @ 60 Mph	0.56
Max +25% -3dB Freq. From Steering Sensitivity @ 60 Mph	1.938	Min. -25% -3dB Frequency From Steering Sensitivity @ 60 Mph	0.66
Max +25% 45 Deg Phase Lag Time @ 60 Mph	288.75	Min. -25% 45 Deg Phase Lag Time @ 60 Mph	94.50
Max +25% Steering Sensitivity @ 75 Mph	2.375	Min. -25% Steering Sensitivity @ 75 Mph	0.59
Max +25% -3dB Freq. From Steering Sensitivity @ 75 Mph	1.938	Min. -25% -3dB Frequency From Steering Sensitivity @ 75 Mph	0.62
Max +25% 45 Deg Phase Lag Time @ 75 Mph	306.25	Min. -25% 45 Deg Phase Lag Time @ 75 Mph	0.15
Yaw/ Steering Wheel Angle		***Yaw/ Steering Wheel Angle***	
Max +25% Yaw Peak Frequency @ 45 Mph	2.1375	Min. -25% Yaw Peak Frequency @ 45 Mph	0.55
Max +25% 45 Deg. Phase Lag Time @ 45 Mph	170	Min. -25% 45 Deg. Phase Lag Time @ 45 Mph	61.50
Max +25% Yaw Peak/Steady State Magnitude @ 45 Mph	1.75	Min. -25% Yaw Peak/Steady State Magnitude @ 45 Mph	0.78
Max +25% Yaw Peak Frequency @ 60 Mph	1.8875	Min. -25% Yaw Peak Frequency @ 60 Mph	0.62
Max +25% 45 Deg. Phase Lag Time @ 60 Mph	168.75	Min. -25% 45 Deg. Phase Lag Time @ 60 Mph	63.00
Max +25% Yaw Peak/Steady State Magnitude @ 60 Mph	2.313	Min. -25% Yaw Peak/Steady State Magnitude @ 60 Mph	0.89
Max +25% Yaw Peak Frequency @ 75 Mph	1.825	Min. -25% Yaw Peak Frequency @ 75 Mph	0.51
Max +25% 45 Deg. Phase Lag Time @ 75 Mph	172.5	Min. -25% 45 Deg. Phase Lag Time @ 75 Mph	63.75
Max +25% Yaw Peak/Steady State Magnitude @ 75 Mph	2.838	Min. -25% Yaw Peak/Steady State Magnitude @ 75 Mph	1.00
Roll /Ay		***Roll /Ay***	
Max +25% Roll Peak Frequency @ 45 Mph	3.363	Min. -25% Roll Peak Frequency @ 45 Mph	0.11
Max +25% Roll Peak/Steady State Magnitude @ 45 Mph	3.15	Min. -25% Roll Peak/Steady State Magnitude @ 45 Mph	0.97
Max +25% Roll Peak Frequency @ 60 Mph	3.363	Min. -25% Roll Peak Frequency @ 60 Mph	0.08
Max +25% Roll Peak/Steady State Magnitude @ 60 Mph	3.263	Min. -25% Roll Peak/Steady State Magnitude @ 60 Mph	0.95
Max +25% Roll Peak Frequency @ 75 Mph	3.413	Min. -25% Roll Peak Frequency @ 75 Mph	0.08
Max +25% Roll Peak/Steady State Magnitude @ 75 Mph	3.013	Min. -25% Roll Peak/Steady State Magnitude @ 75 Mph	0.75
Max +25% Yaw Overshoot (.5G @ 60 Mph)	2.75	Min. -25% Yaw Overshoot (.5G @ 60 Mph)	0.02
Max +25% Yaw Overshoot (.7G @ 75 Mph)	6.813	Min. -25% Yaw Overshoot (.7G @ 75 Mph)	1.56
Max +25% Understeer Gradient (<.3 G's)	8.125	Min. -25% Understeer Gradient (<.3 G's)	1.35
Max +25% Roll Gradient	9.25	Min. -25% Roll Gradient	2.03

From Ford Provided Data

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Number of Vehicle in Sample	27
Average Production Year	1995

Mean +3σ Wheelbase	121.47	Mean -3σ Wheelbase	84.67
Mean +3s Curb Weight	4188.55	Mean -3s Curb Weight	1358.21
Mean +3s Test Weight	4638.19	Mean -3s Test Weight	1688.40
Mean +3s Steering Ratio	21	Mean -3s Steering Ratio	12
Mean +3s Off Center Yaw Gain @ 30 Mph	-	Mean -3s Off Center Yaw Gain @ 30 Mph	-
Mean +3s Steering Torque Gradient @ 30 Mph	254.47	Mean -3s Steering Torque Gradient @ 30 Mph	58.62
Mean +3s Torsional Rate @ 30 Mph	1.49	Mean -3s Torsional Rate @ 30 Mph	0.31
Mean +3s Off Center Yaw Gain @ 45 Mph	42.09	Mean -3s Off Center Yaw Gain @ 45 Mph	15.51
Mean +3s Steering Torque Gradient @ 45 Mph	249.32	Mean -3s Steering Torque Gradient @ 45 Mph	67.56
Mean +3s Torsional Rate @ 45 Mph	2.29	Mean -3s Torsional Rate @ 45 Mph	0.59
Mean +3s Off Center Yaw Gain @ 60 Mph	45.90	Mean -3s Off Center Yaw Gain @ 60 Mph	9.97
Mean +3s Steering Torque Gradient @ 60 Mph	260.14	Mean -3s Steering Torque Gradient @ 60 Mph	69.11
Mean +3s Torsional Rate @ 60 Mph	2.95	Mean -3s Torsional Rate @ 60 Mph	0.78
Mean +3s Off Center Yaw Gain @ 75 Mph	43.51	Mean -3s Off Center Yaw Gain @ 75 Mph	6.82
Mean +3s Steering Torque Gradient @ 75 Mph	280.46	Mean -3s Steering Torque Gradient @ 75 Mph	25.26
Mean +3s Torsional Rate @ 75 Mph	3.40	Mean -3s Torsional Rate @ 75 Mph	0.82
Frequency Response Tests		**Frequency Response Tests**	
Ay/ Steering Wheel Angle		***Ay/ Steering Wheel Angle***	
Mean +3s Steering Sensitivity @ 45 Mph	1.30	Mean -3s Steering Sensitivity @ 45 Mph	0.50
Mean +3s -3dB Frequency From Steering Sensitivity @ 45 Mph	1.66	Mean -3s -3dB Frequency From Steering Sensitivity @ 45 Mph	0.66
Mean +3s 45 Deg Phase Lag Time @ 45 Mph	268.07	Mean -3s 45 Deg Phase Lag Time @ 45 Mph	31.55
Mean +3s Steering Sensitivity @ 60 Mph	1.72	Mean -3s Steering Sensitivity @ 60 Mph	0.59
Mean +3s -3dB Frequency From Steering Sensitivity @ 60 Mph	1.63	Mean -3s -3dB Frequency From Steering Sensitivity @ 60 Mph	0.65
Mean +3s 45 Deg Phase Lag Time @ 60 Mph	256.82	Mean -3s 45 Deg Phase Lag Time @ 60 Mph	91.18
Mean +3s Steering Sensitivity @ 75 Mph	2.05	Mean -3s Steering Sensitivity @ 75 Mph	0.63
Mean +3s -3dB Frequency From Steering Sensitivity @ 75 Mph	1.64	Mean -3s -3dB Frequency From Steering Sensitivity @ 75 Mph	0.65
Mean +3s 45 Deg Phase Lag Time @ 75 Mph	314.20	Mean -3s 45 Deg Phase Lag Time @ 75 Mph	35.73
Yaw/ Steering Wheel Angle		***Yaw/ Steering Wheel Angle***	
Mean +3s Yaw Peak Frequency @ 45 Mph	2.05	Mean -3s Yaw Peak Frequency @ 45 Mph	0.44
Mean +3s 45 Deg. Phase Lag Time @ 45 Mph	140.26	Mean -3s 45 Deg. Phase Lag Time @ 45 Mph	61.90
Mean +3s Yaw Peak/Steady State Magnitude @ 45 Mph	1.47	Mean -3s Yaw Peak/Steady State Magnitude @ 45 Mph	0.91
Mean +3s Yaw Peak Frequency @ 60 Mph	1.69	Mean -3s Yaw Peak Frequency @ 60 Mph	0.61
Mean +3s 45 Deg. Phase Lag Time @ 60 Mph	141.05	Mean -3s 45 Deg. Phase Lag Time @ 60 Mph	66.57
Mean +3s Yaw Peak/Steady State Magnitude @ 60 Mph	1.97	Mean -3s Yaw Peak/Steady State Magnitude @ 60 Mph	0.97
Mean +3s Yaw Peak Frequency @ 75 Mph	1.68	Mean -3s Yaw Peak Frequency @ 75 Mph	0.61
Mean +3s 45 Deg. Phase Lag Time @ 75 Mph	143.52	Mean -3s 45 Deg. Phase Lag Time @ 75 Mph	68.10
Mean +3s Yaw Peak/Steady State Magnitude @ 75 Mph	2.53	Mean -3s Yaw Peak/Steady State Magnitude @ 75 Mph	1.09
Roll /Ay		***Roll /Ay***	
Mean +3s Roll Peak Frequency @ 45 Mph	3.70	Mean -3s Roll Peak Frequency @ 45 Mph	0.82
Mean +3s Roll Peak/Steady State Magnitude @ 45 Mph	3.92	Mean -3s Roll Peak/Steady State Magnitude @ 45 Mph	0.09
Mean +3s Roll Peak Frequency @ 60 Mph	3.75	Mean -3s Roll Peak Frequency @ 60 Mph	0.82
Mean +3s Roll Peak/Steady State Magnitude @ 60 Mph	4.00	Mean -3s Roll Peak/Steady State Magnitude @ 60 Mph	-0.04
Mean +3s Roll Peak Frequency @ 75 Mph	3.95	Mean -3s Roll Peak Frequency @ 75 Mph	0.52
Mean +3s Roll Peak/Steady State Magnitude @ 75 Mph	4.00	Mean -3s Roll Peak/Steady State Magnitude @ 75 Mph	-0.38
Mean +3s Yaw Overshoot (.5G @ 60 Mph)	2.21	Mean -3s Yaw Overshoot (.5G @ 60 Mph)	-0.94
Mean +3s Yaw Overshoot (.7G @ 75 Mph)	6.82	Mean -3s Yaw Overshoot (.7G @ 75 Mph)	-0.12
Mean +3s Understeer Gradient (<.3 G's)	6.16	Mean -3s Understeer Gradient (<.3 G's)	0.20
Mean +3s Roll Gradient	8.18	Mean -3s Roll Gradient	1.37

3.0 SUBSYSTEM REQUIREMENTS

1 ## - Requirements Review

Subsystem Requirements (Excluding mechanical subsystem)

Draft – 11/26/96

2 ## - Introduction

- **This presentation covers the requirement flow down to the subsystem level**
- **In general, compliance with Exhibit I is assumed**
  - Deviations will be noted
- **Note -these requirements are mostly based on the original requirements in Exhibit** I
  - The results of the analysis performed **by** MRA and MDI have not been fully incorporated yet

3 ## - Outline

- **Electronics**
- **Control Computer**
  - Critical Data Items
  - Graphical Users Interface
- **Sensors**
- **Steer-by-wire**
- **Rear Steer**
- **Steering Feel**
- **Brake-by-wire**
- **Brake Feel**
- **Automatic Braking System (ABS)**
- **Throttle-by-wire**
- **Throttle Feel**
- **Semi Active Suspension**
- **Roll Control**
- **Subsystem I/F Modules**
- **Watch Dog Module**
- **Mechanical Back-ups**
- **User Supplied Equipment**
- **Electrical Power**

4 ## - Electronics

- **In general, all of the VDTV electronics have to meet the following requirements**
  - Except for embedded electronics, any element must be removable within 15 minutes
  - Must operate with ambient conditions from -20 deg. C to 38 deg. C
    - assuming interior temp. ranges from 20 deg. C to 32 deg C after warm up/cool down
  - Electromagnetic Compatibility (EMC) to an E-field strength of 100 V/meter

5 - Control Computer

- **General**
  - Accepts IBM PC compatible 3.5” floppy media
  - Maintain configuration information
    - per 3511.3 (Sensor Configuration)
  - Monitor all electrical system voltage level
- **Safety**
  - Generate system health and status (SHS) **message** every 10 millisec
  - Observe all safety critical control and sensor information for out of range numbers every IO millisec per 4.4.1.2 (b)
    - Also check data slope of critical items to identify unsafe operation per 4.4.1.2 (c)
  - Indicate failures and engage mechanical back-ups where appropriate
  - Safety critical data must be checked before usage by control algorithms
- **Pvr**
  - Store and issue the time series of control commands to perform the maneuvers defined in 3.5.1.1
  - Compare the actual results with the upper and lower performance bounds and issue a health message within 30 seconds

6 - Critical Data Items

- **The currently identified critical data items include**
  - Vehicle Velocity
  - Lateral Acceleration
  - Front Rack Position
  - Rear Rack Position

7 - Graphical Users Interface (GUI)

- **Capabilities**
  - Invoke the various PVTs
  - Handle updates of dynamic performance desired from keyboard or floppy
  - Handle updates of control coefficients from keyboard or floppy
  - Handle updates of control algorithms from floppy
  - Display system health and status
    - Data Limit failures per 4.4.1.2 (b) iii and (c) iii

8 - Sensors

- **Note – In most instances the sensors required will be embedded in the various dynamic subsystems**

9 - Steer-by-wire

- **Per Exhibit 1, Section 4.3.1**
- MRA **Recommendations**

- Minimize friction
- Add viscous damper on steer angle
- Minimize compliances
- Add steer angle feedback
- Measure slideslip angle, lateral acceleration, and yaw accel/rate to control:
  - understeer
  - acceleration rise time
  - percent overshoot in yaw response
  - time to peak yaw response

- **Depending on compliances achievable, bandwidth will be at least 15 Hz**
  - Could be as high as 25 Hz

10 - Rear Steer

- **Per Exhibit 1, Section 4.3.7**

11 - Steering Feel

- **Per Exhibit 1, Section 4.3.2**

12 - Brake-by-wire

- **Per Exhibit** 1, Section 4.3.3
- **Deviations**
  - Minimum deceleration of 0.005 g not obtainable while maintaining FMVSS braking requirements

13 - Brake Feel

- **Per Exhibit 1, Section 4.3.4**
- **Deviations**
  - Emulation Range
    - Still under negotiation with Delphi
  - Driver Attention Pulses
    - Still under negotiation with Delphi

14 - Automatic Braking System

- **Per Exhibit 1, Section 4.3.9**
- **Deviations**
  - No Slip ratio control from laptop computer
- **Additions**
  - Yaw control
  - Traction control

15 - Throttle-by-wire

- **Per Exhibit I, Section 4.3.5**

16 - Throttle Feel

- Per Exhibit 1, Section 4.3.6

17 - Semi Active Suspension

- Per Exhibit 1, Section 4.3.6

18 - Roll Control

- Per Exhibit 1, Section 7.1.2
- MRA Recommendations
  - Measure roll angle and roll acceleration to decouple roll from yaw/slideslip

19 - Subsystem I/F Modules

- Provide CAN interface to system control bus
  - J1939 compliant (250Kbps)
- Provide digital and analog interface to dynamic subsystems and control computer
- Read all dynamic sensor information at 40 Hz or higher
  - Provide 20 Hz sensor bandwidth
- Generate all dynamic actuator control signals at 40 Hz or higher
  - Provide 20 Hz control bandwidth

20 - Watch Dog Module

- Safety
  - Protect from single point faults
  - Observe system health and status (SHS) messages
  - Act on failure reports and lack of SHS message
- Action
  - Control electro-mechanical relays for each of the mechanical back-up systems
  - Back-ups are positively disengaged – I.e. default is engaged
  - Power fail mode results in all back-ups engaging
  - Signal occupants of any failures

21 – Mechanical Back-ups

- Must be engaged electronically within 50 millisec after a failure detection

22 - User Supplied Equipment

- Four interface points will be present on the VDTV
  - Front, Rear, and both sides
  - Per Exhibii I, section 4.8.2.1
- Data interface via an independent CAN bus
- Power Interface
  - +/-12Volt@ 1 amp

– 5 Volt @ 0.5 amp

23 - **Electrical Power**

- **Per Exhibit 1, Section 4.6**
  - strike 4.6.4 (e)

Sensors

- **Note -- In most instances the sensors required will be embedded in the various dynamic subsystems**

Sensor	Bandwidth (Hz)	Accuracy	Range	Resolution
Lateral Acceleration	20			
Front Rack Position	20	0.02 deg.		
Steering wheel position	20			
Steering Wheel Angle	20			
Longitudinal Acceleration	20			0.01 g
Vehicle Velocity				
Yaw Acceleration				
Yaw Velocity				
Wheel Motion -- Vertical				
Voltmeters	NA			
Roll Angle	20			
Roll Acceleration	20			
Slideslip Angle	20			
Slideslip Rate	20			

DESIGN ANALYSIS REVIEW

1. STEER SUBSYTEM DESIGN ISSUES

2. VEHICLE DATA
   * WEIGHT, BALANCE AND INERTIA ESTIMATES
   *ACTIVE VDTV VS TRANSPORT MODE

3. LINEAR HANDLING BEHAVIOR
   * EQUATIONS OF MOTION
   * STATIC SENSITMTIES
     & UNDERSTEER GRADIENT
   * DYNAMIC CHARACTERISTICS

4. SIMULATION RESULTS
   ROLL DECOUPLING
   SIDESLIP GRADIENT
   UNDERSTEER GRADIENT
   YAW OVERSHOOT
   ACCELERATION RISE TIME
   BANDWIDTH EFFECT
   REAR STEER ANGLE REQUIREMENT

5. CONCLUSIONS ON HANDLING METRICS

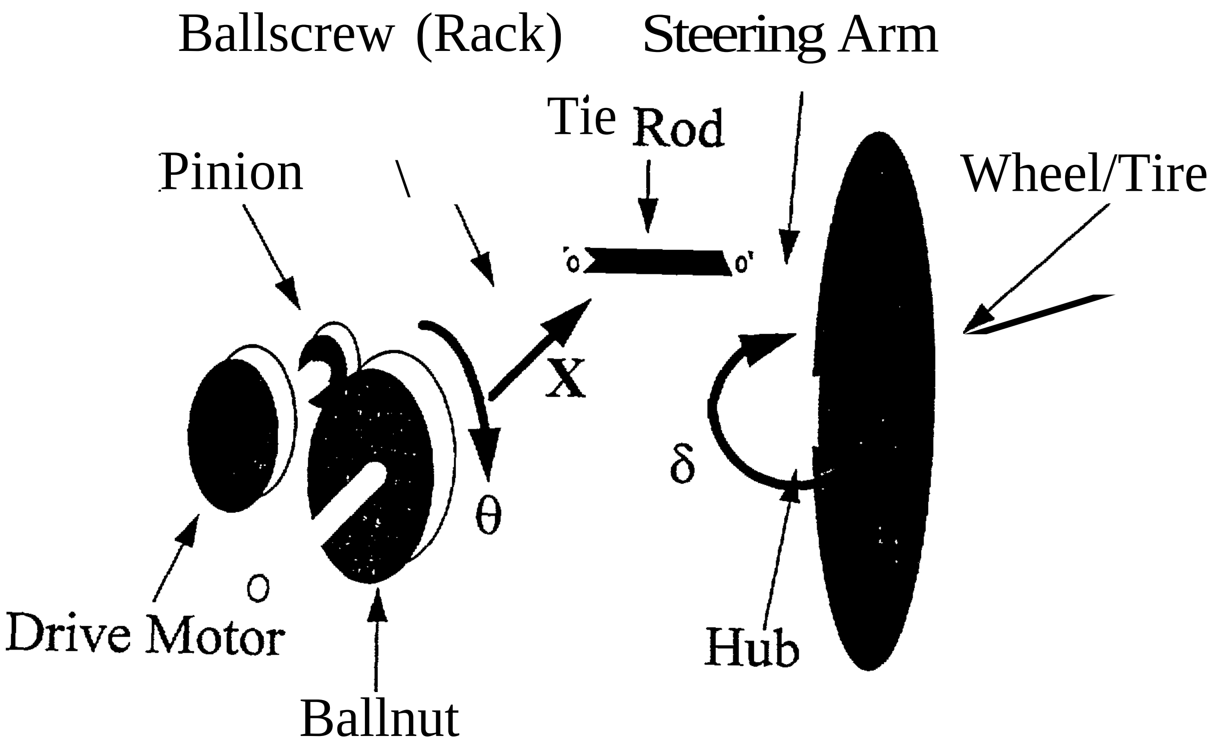
6. SUMMARY

LINEAR SYSTEM ANALYSIS OF STEERING SUBSYSTEM

PURPOSE:

- 0 ASSESS NEED FOR EXTERNAL MECHANICAL STEER DAMPER
- 0 DETERMINE UTILITY OF STEER ANGLE FEEDBACK
- 0 ESTIMATE ANTICIPATED BANDWIDTH
- 0 DEVELOP SIMPLE MODEL FOR VEHICLE SIMULATION

SCHEMATIC OF STEER CONTROL SYSTEM



EQUATIONS OF MOTION OF CONTROL SYSTEM:

MOMENTS ABOUT STEER AXIS:

$$I_w\ (d^2\delta/dt^2) + C_{D\delta}\ (d\delta/dt) + KR^2\ \delta - KRr_m\theta =$$

$$- CSgn\ (d\delta/dt) + (SAT + T_mFy)$$

TORQUE ON BALLNUT:

$$I\ \ (d^2\theta/dt^2) + K_D\,(d\theta/dt) + (K_\theta + Kr_m{}^2)\ \theta + K_{D\delta}\ \ (d\delta/dt)$$

$$+ (K_\delta - KRr_m)\ \delta\ =\ K_\delta\ \ \delta_C - B\ r_m\,Sgn\ (d\theta/dt)$$

WHERE: δ = STEER ANGLE

δ_C = COMMANDED STEER ANGLE

θ = BALLNUT ROTATION ANGLE

I_W = MOMENT OF INERTIA OF MOTOR AND BALLNUT

I = MOMENT OF INERTIA OF TIRES, WHEELS AND HUBS ABOUT STEER AXIS

$C_{D\delta}$ = PHYSICAL STEER DAMPING

K = EFFECTIVE STIFFNESS BETWEEN TIE ROD END AND BODY - CORRESPONDS TO STEER COMPLIANCE

K_{δ} = STEER ANGLE POSITION FEEDBACK GAIN

$K_{D\delta}$ = STEER ANGLE RATE FEEDBACK GAIN

K_{θ} = BALLNUT ROTATION FEEDBACK GAIN

K_D = BALLNUT (TOTAL) RATE FEEDBACK GAIN

R = EFFECTIVE STEERING ARM RADIUS

r_m = RATIO OF RACK DISPLACEMENT TO BALLNUT ROTATION ANGLE

B = COULOMB FRICTION BETWEEN BALLNUT AND BALLSCREW

C = COULOMB FRICTION ABOUT STEER AXIS

SAT = TIRE SELF ALIGNING TORQUE

T_m = MECHANICAL TRAIL (CASTER TRAIL)

F_y = TIRE LATERAL FORCE

WITH ZERO STEER FEEDBACK AND NO MECHANICAL STEER ANGLE RATE DAMPER:

$$I_w\ (d^2\delta/dt^2) + KR^2\ \delta - KRr_m\theta =$$

$$- CSgn\ (d\delta/dt) + (SAT + T_mFy)$$

$$I\ (d^2\theta/dt^2) + K_D\,(d\theta/dt) + (K_\theta + Kr_m{}^2)\ \theta\ \ - KRr_m)\ \delta\ =$$

$$- B\ r_m\,Sgn\ (d\theta/dt)$$

<u>THE KRr$_m$ TERMS MAKE THE SYSTEM UNSTABLE</u>

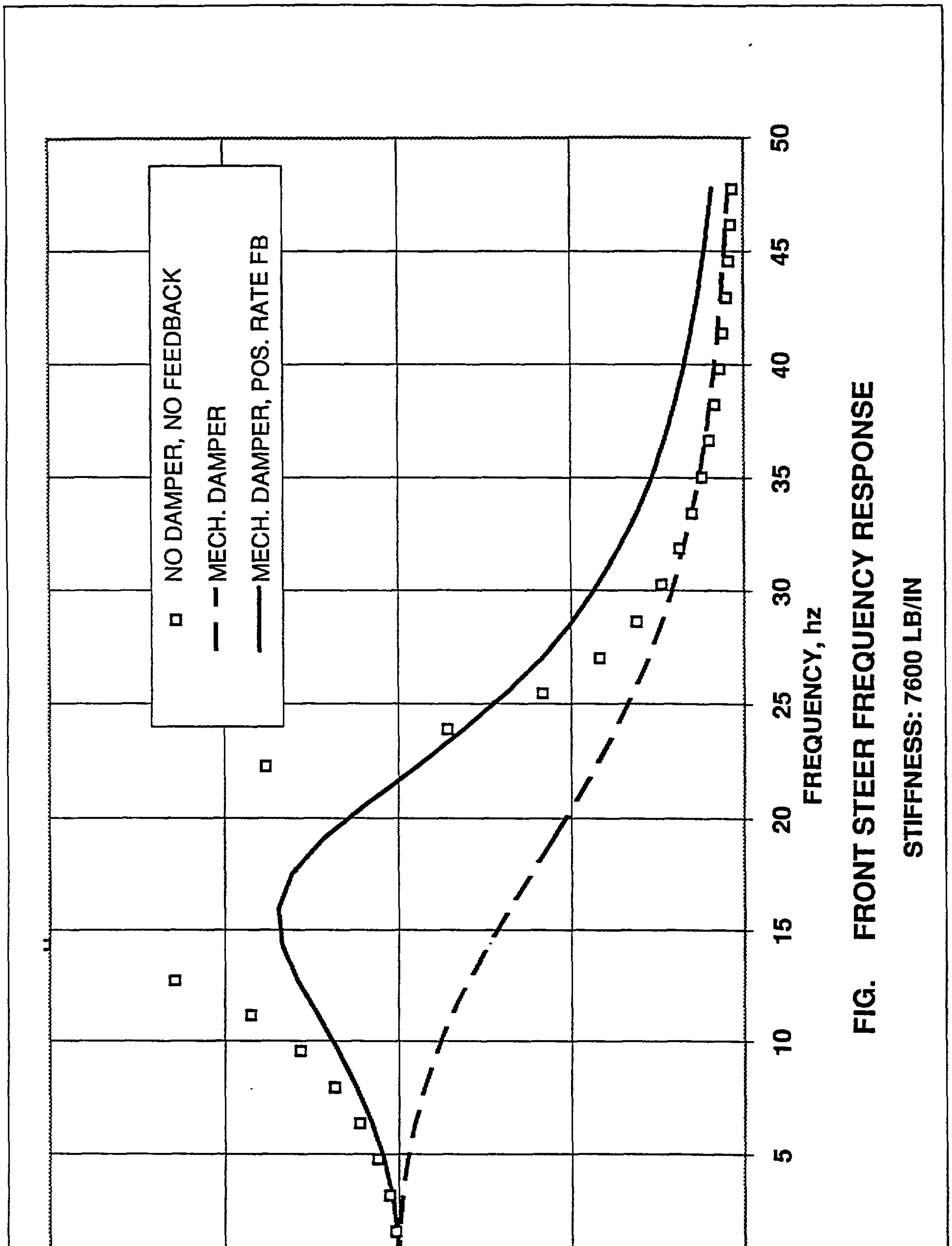


FIG. FRONT STEER FREQUENCY RESPONSE

STIFFNESS: 7600 LB/IN

VDC13.XLS

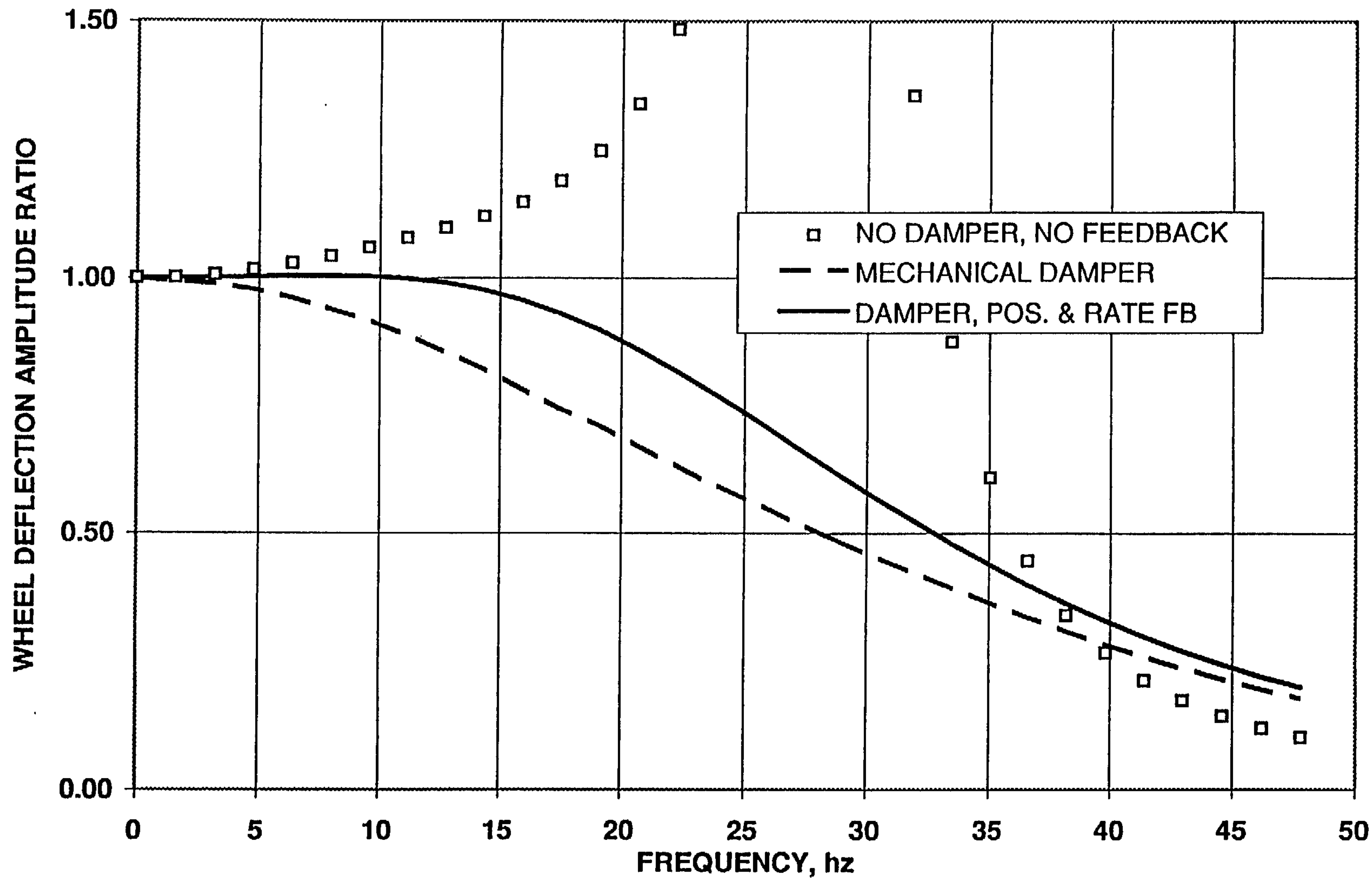


FIG. REAR STEER FREQUENCY RESPONSE

STIFFNESS: 19,000 LB/IN

VDC46.XLS

RECOMMENDATIONS

0 REDUCE FRICTION TO MINIMUM

0 ADD VISCOUS DAMPER ON STEER ANGLE

0 PROVIDE FOR REDUCED COMPLIANCES, ESPECIALLY ON THE FRONT

0 ADD STEER ANGLE AND STEER ANGLE RATE FEEDBACK

0 UPDATE ANALYSIS AS MORE ACCURATE PARAMETER DATA BECOME AVAILABLE

CONCLUSIONS

0 WELL DAMPED STEER RESPONSE IS PRACTICAL

0 PRECISE CONTROL OF STEER ANGLE IS AVAILABLE BY STEER ANGLE AND RATE FEEDBACK

0 BANDWIDTHS BETWEEN 21 AND 25 hz CAN BE OBTAINED, DEPENDING ON COMPLIANCES.

WEIGHT AND INERTIA DATA

ITEM	WEIGHT	HEIGHT	DISTANCE	RADII OF GYRATION RHO XXS	RHO ZZ	INERTIAS IZ	IXS
	W	Z	X	ABOUT OWN CG		INCL. XFER	
	LB	IN	IN	IN	IN	FT-LB-SEC^2	
VDTV-ESTIMATED							
FRONT UNSPRUNG	240 [220]	13	0	30.44	29.52	129.4 [123.2]	52.3 [47.9]
REAR UNSPRUNG	200 [220]	13	106.32	31.2	29.52	225.5 [240.6]	45.6 [50.1]
TAURUS SPRUNG	3122	22.29	38.4	23.41	49.33	1693.1	369.2
1. EXTRA BATTERY	40	26	0 [66]	3	3	14.1 [5.2]	0.2 [0.1
2. ANTI-ROLL BAR HYDRAULICS	0						
3. FRONT ELECTRIC STEERING	50	11	8	5	3	11.4 [12.2]	1.6
4. REAR ELECTRIC STEERING	50	11	98	5	3	36.0 [34.5]	1.6
5. FRONT ACTIVE ANTI-ROLL BAR	40	11	8	5	3	9.1 [9.8]	1.3
6. FRONT ACTIVE ANTI-ROLL BAR	40	11	98	5	3	28.8 [27.6]	1.3
7. COMPUTERS (REAR SEAT)	40	24	66	3	3	5.8 [5.2]	0.1
8. LAPTOP (FRONT DASH)	10	30	30	2	2	0.2 [0.3]	0.1
9. ROLL CAGE	100	36	50	40	30	21.4 [21.0]	38.6 [38.7]
10.INSTRUMENTATON	40	22	40	50	20	3.5	21.6
11.MISCELLANEOUS	28	22	40	50	20	2.4	15.1
SPRUNG	3560	22.18	38.40			1825.7 [1814.8]	450.8 [450.8]
TOTAL	4000	21.17	40.34 [41.53]	25.22	50.27	2180.6 [2178.7]	548.8 [548.9]

NOTE: [XXXX] REFERS TO REVISED WEIGHTS AND TRANSPORT MODE

VDTV6.XLS

WEIGHT AND INERTIA DATA

			AS SIMULATED	TRANSPORT MODE
HEIGHT TO TOTAL CG	IN		21.17	21.17
FRONT ROLL CENTER HEIGHT	IN		1.82	1.82
REAR ROLL CENTER HEIGHT	IN		0.26	0.26
ROLL AXIS HEIGHT AT CGS	IN		0.83	0.83
HT. SPRUNG CG TO ROLL AXIS	IN		20.94	20.94
IX-SPRUNG MASS (OWN CG)	FT-LB-SEC^2		450.8	450.8
XFER TERM TO ROLL AXIS	FT-LB-SEC^2		350.3	350.3
TOTAL IXS ABOUT ROLL AXIS	FT-LB-SEC^2		801 #	801
TOTAL IZ ABOUT TOTAL CG	FT-LB-SEC^2		2181 *	2179
FRONT AXLE TO CG = a	IN		40.34	41.53
REAR AXLE TO CG = b	IN		65.66	64.47
PERCENT WEIGHT ON FRONT	%		61.9	60.8
TRACK WIDTH	IN		61.2	61.20
FRONT:				
UNSPRUNG WEIGHT	LB		240	220
CG HEIGHT	IN		13	13
TOE ANGLE, DEG	DEG		-0.02	0
CASTER TRAIL	IN		1.03	1.030
ROLL CAMBER			0.741	0.741
ROLL STEER			0	0
LAT. FORCE COMPL. STEER (MUF)	DEG/LB		-0.000531	-0.000531
LAT. FORCE COMPL. CAMBER (DGDSF)	DEG/LB		-0.000668	-0.000668
SAT COMPL. STEER (ETAF)	DEG/IN-LB		0.000302	0.000302
SAT COMPL. CAMBER (DGDAF)	DEG/IN-LB		0.000014	0.000014
ROLL RATE (TOTAL)	IN-LB/DEG		10490	10490
REAR:				
UNSPRUNG WEIGHT	LB		200	220
CG HEIGHT	IN		13	13
TOE ANGLE, DEG	DEG		0.016	0
CASTER TRAIL			NA	
ROLL CAMBER			0.894	0.741
ROLL STEER			0	0
LAT. FORCE COMPL. STEER (MUR)	DEG/LB		0.000051	-0.0002
LAT. FORCE COMPL. CAMBER (DGDSR)	DEG/LB		-0.000156	-0.000156
SAT COMPL. STEER (ETAR)	DEG/IN-LB		0.00012	0.00012
SAT COMPL. CAMBER (DGDAR)	DEG/IN-LB		0.000006	0.000006
ROLL RATE (TOTAL)	IN-LB/DEG		7063	7063
	# 899 FT-LB-SEC^2 USED IN CALCULATIONS			
	* 2199 FT-LB-SEC^2 USED IN CALCULATIONS			

VDTV6.XLS

MAJOR DIFFERENCES BETWEEN BASELINE VDTV AND TRANSPORT MODE

O WEIGHT AND BALANCE REVISIONS

* EXTRA BATTERY TO REAR FLOOR

* EQUAL UNSPRUNG WEIGHTS

O ZERO TOE ANGLES (NO EFFECT)

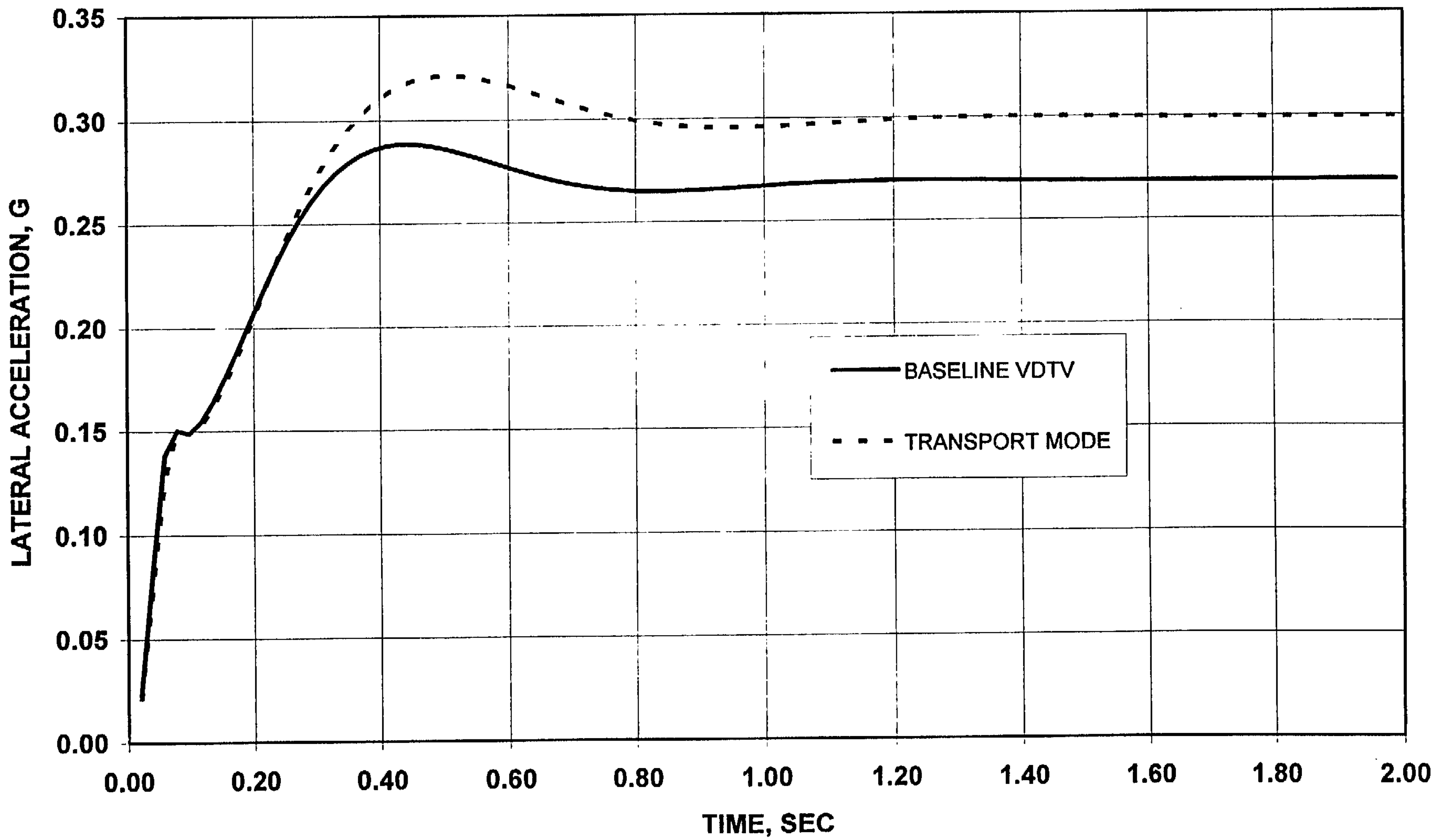
O SAME ROLL STEER FRONT AND REAR

LATERAL FORCE
O REAR ~~SELF ALIGNING TORQUE~~ COMPLIANCE STEER = 1/3 OF FRONT VALUE

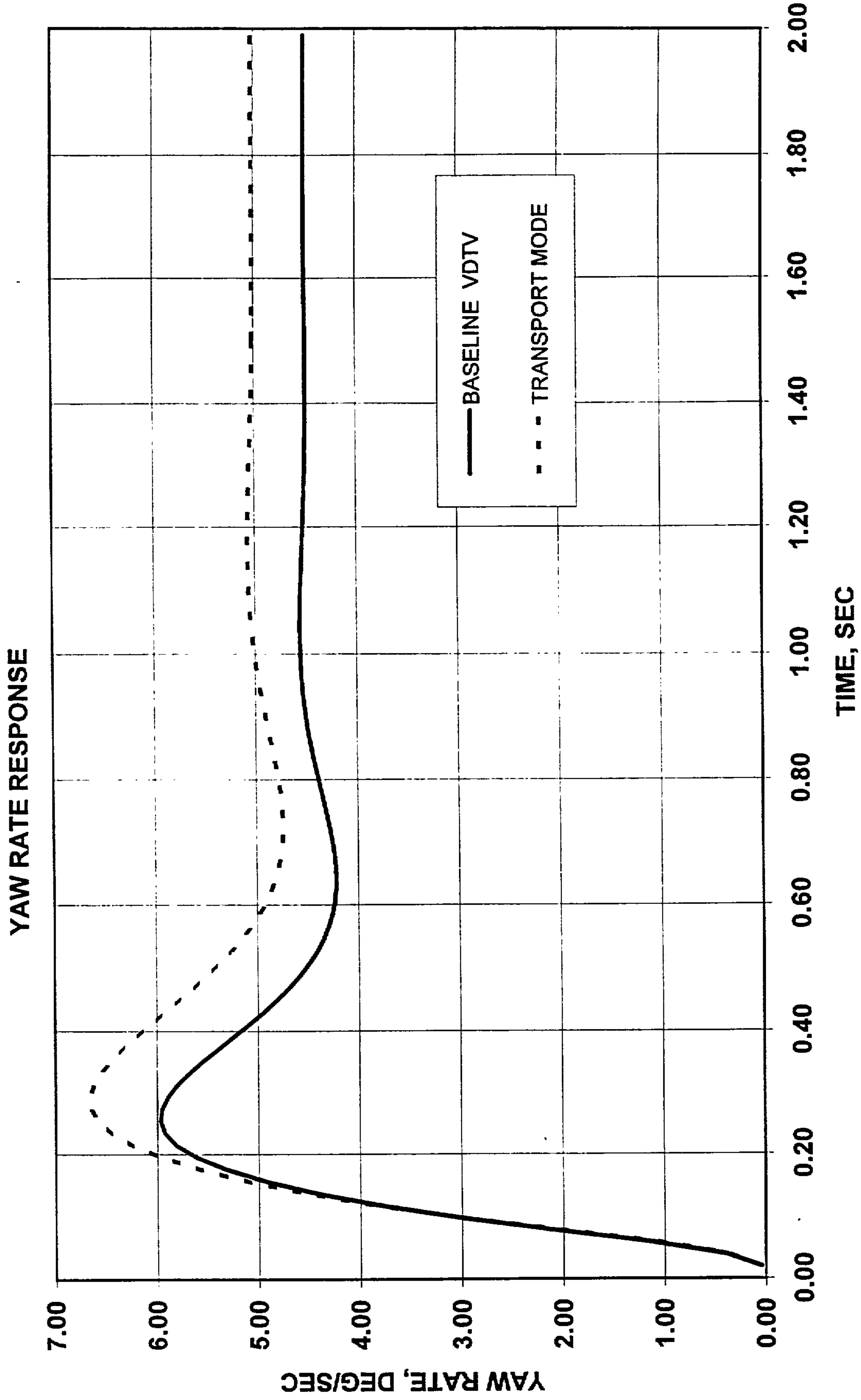
RESULT: UNDERSTEER GRADIENT DECREASE FROM 3.31 TO 2.86 DEG/G

COMPARISON OF BASELINE VDTV WITH TRANSPORT MODE

LATERAL ACCELERATION RESPONSE



COMPARISON OF BASELINE VDTV WITH TRANSPORT MODE



COMPARISON OF BASELINE VDTV WITH TRANSPORT MODE

SIDESLIP ANGLE RESPONSE

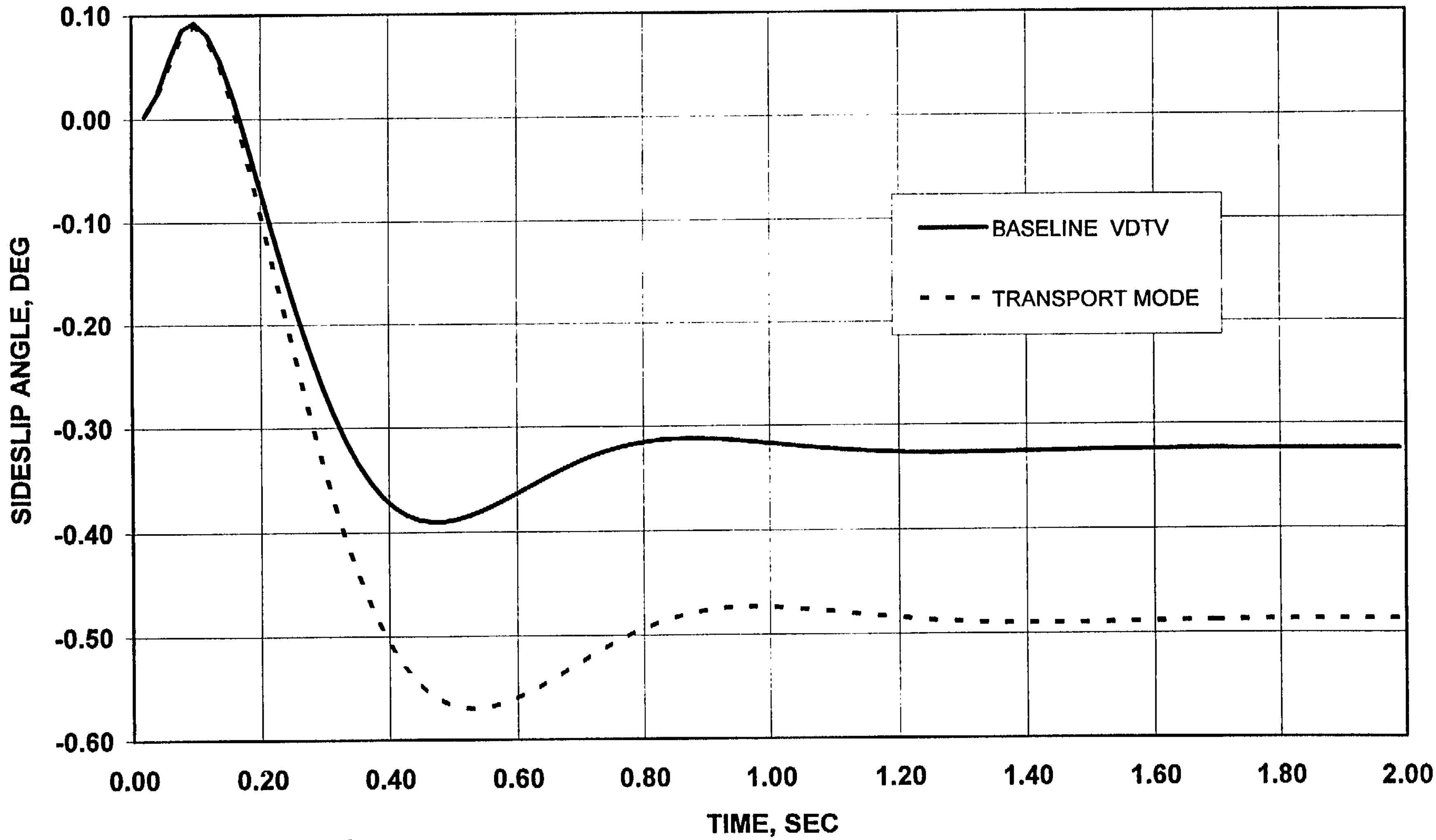


FIG.

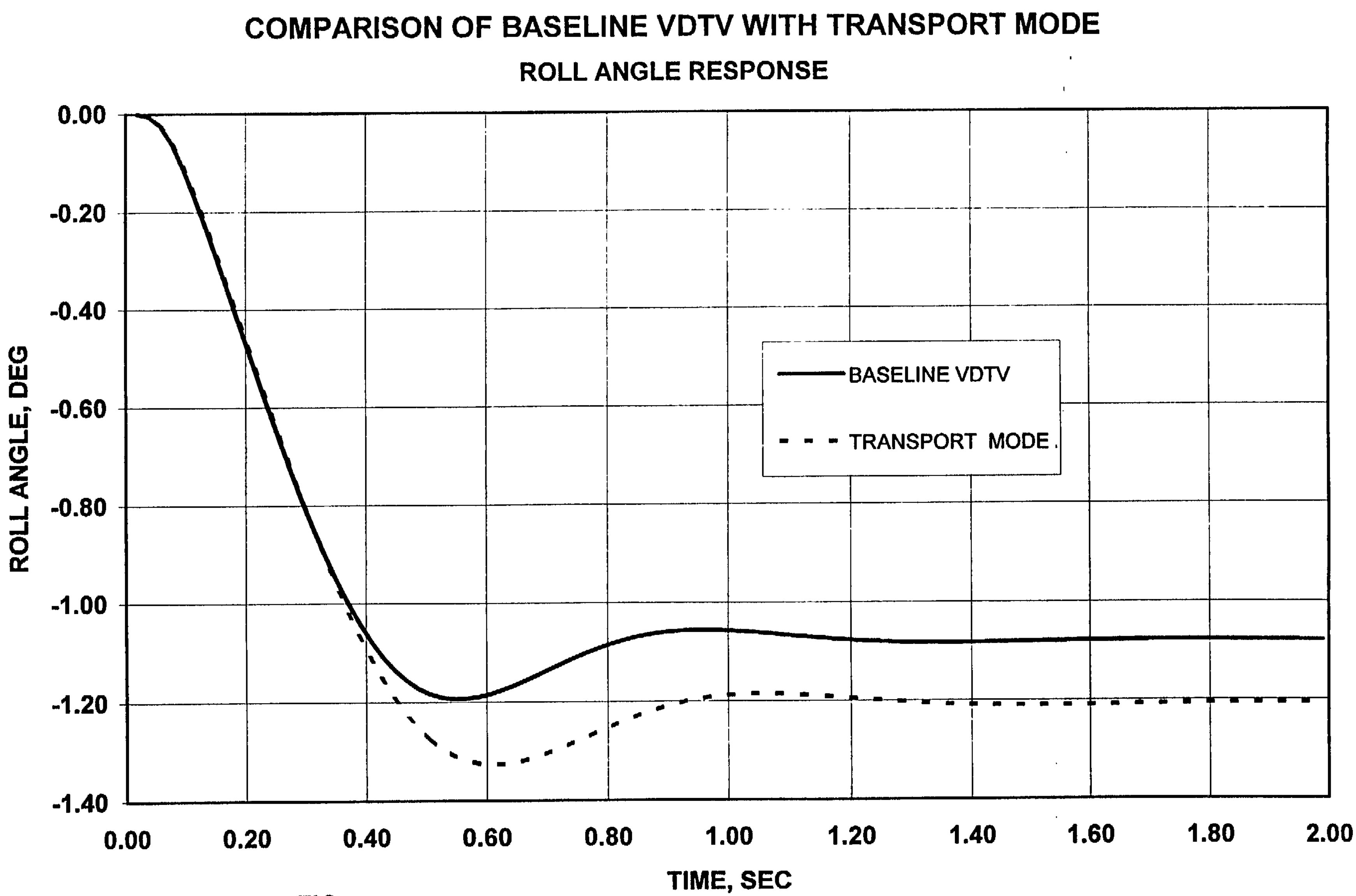

COMPARISON OF BASELINE VDTV WITH TRANSPORT MODE
ROLL ANGLE RESPONSE
0.00
-0.20
-0.40
-0.60
-0.80
-1.00
-1.20
-1.40
ROLL ANGLE, DEG
BASELINE VDTV
TRANSPORT MODE
0.00
0.20
0.40
0.60
0.80
1.00
1.20
1.40
1.60
1.80
2.00
TIME, SEC

FIG.

LINEAR HANDLING BEHAVIOR

EQUATIONS OF MOTION: (Ignoring aerodynamic terms)

$$mV(d\beta/dt + r) + m_s h(dp/dt) =$$

$$Y_\beta \beta + Y_r r + Y_\phi \phi + Y_{\delta F}\, \delta_F + Y_{\delta R}\, \delta_R$$

$$I_z(dr/dt) + I_{xz}(dp/dt) =$$

$$N_\beta \beta + N_r r + N_\phi \phi + N_{\delta F}\, \delta_F + N_{\delta R}\, \delta_R$$

$$I_x(dp/dt) + I_{xz}(dr/dt) + m_s hV(d\beta/dt + r) =$$

$$L_\phi \phi + L_p\, (d\phi/dt)$$

STEADY STATE RESPONSE RATIOS

STEERING SENSITIVITY (G PER 100 DEG, SWA)

$$GPER = (a_y / 100\ \delta_{sw}) = -\ A*100*V/(B*57.3*g*SR)$$

WHERE: $A = (Y_\beta N_{\delta F} - N_\beta Y_{\delta F})$

$$B = (-mVN_\beta + N_\beta Y_r' - Y_\beta N_r')$$

$$Y_r' = Y_r + m_s h_s V\ Y_\phi / L_\phi$$

$$N_r' = N_r + m_s h_s V\ N_\phi / L_\phi$$

UNDERSTEER GRADIENT:

$$U/G = (\delta_{sw} / SR) / a_y - 57.3*(gL/V^2)$$

$$= (100*SR / GPER) - 57.3*(gL/V^2)$$

OR: $$U/G = (1/SR)*(\partial\ \delta_{SW} / \partial\ a_{Yo}) - 57.3*gL/V^2$$

ALSO:

$a_{Yo} / (\delta_{SW} / SR) =$

$$[g/V]*[\, -mVN_{\beta} + N_{\beta}\, Y_r' - Y_{\beta}N_r' \,] \,/\, [\, Y_{\beta}N_{\delta F} - N_{\beta}Y_{\delta F} \,]$$

FOR THE "NORMAL" CAR:

$$[\, N_{\beta}\, Y_r - Y_{\beta}N_r \,] \,/\, [\, Y_{\beta}N_{\delta F} - N_{\beta}Y_{\delta F} \,] = L / V \qquad (1)$$

(WHEELBASE / SPEED)

SO THAT (IN G PER RADIAN):

$a_{Yo} / (\delta_{SW} / SR) =$

$$\underbrace{[g/V]*[\, -mVN_{\beta} \,] \,/\, [\, Y_{\beta}N_{\delta F} - N_{\beta}Y_{\delta F} \,]}_{\text{UNDERSTEER GRADIENT TERM}} - gL/V^2$$

BUT, WHEN USING FEEDBACK TO CHANGE U/G, EQUATION (1) <u>DOES NOT NECESSARILY HOLD</u>

THUS TO VARY THE UNDERSTEER GRADIENT

HOLD BOTH $[Y_\beta N_{\delta F} - N_\beta Y_{\delta F}]$ AND $[N_\beta Y_r - Y_\beta N_r]$

CONSTANT.

THIS PRESERVES THE gL/V^2 (ACKERMANN) TERM

WHILE CHANGING N_β TO VARY THE UNDERSTEER

GRADIENT.

WITH THIS APPROACH RESPONSES CAN RESEMBLE

THOSE OF A CAR WITH LARGE POSITIVE OR

NEGATIVE UNDERSTEER GRADIENT

YAW RATE SENSITIVITY:

$$r_o / \delta_{SW} = (g/V)^* (a_y / \delta_{SW})$$

SIDESLIP SENSITIVITY:

$$\beta_o / (\delta_{SW} / SR) = [mVN_{\delta F} - N_{\delta F} Y_r' + Y_{\delta F} N_r'] / B$$

SIDESLIP GRADIENT:

β_o / a_{Yo} =

$$[g / V]*[mVN_{\delta F} - N_{\delta F} Y_r' + Y_{\delta F} N_r'] / [Y_\beta N_{\delta F} - N_\beta Y_{\delta F}]$$

ROLL GRADIENT:

$$\phi / a_{Yo} = W_S h / L_\phi$$

DYNAMIC RESPONSE BEHAVIOR

YAW-SIDESLIP UNDAMPED NATURAL FREQUENCY:
(TWO DEGREE-OF-FREEDOM MODEL)

$$\omega_n^2 = (A / I_z W) * (U/G / 57.3 + gL/ V^2)$$

$$= (A / I_z W) * (a_Y / \delta_{SW})*(SR/57.3)$$

DAMPING:

$$2\zeta\, \omega_n = -\, (N_r / I_Z + Y_\beta / mV)$$

NORMALIZED YAW RATE RESPONSE:

$$r(s)/r_0 = (1+ \tau_r s) / [1+(2\zeta / \omega_n)s + (1/ \omega_n^2) s^2]$$

NORMALIZED SIDESLIP RESPONSE:

$$\beta(s) / \beta_0 = (1+ \tau_\beta s) / [1+(2\zeta / \omega_n)s + (1/ \omega_n^2) s^2]$$

(r_0, β_0 are the steady state responses)

NUMERATOR TIME CONSTANTS:

$$\tau_r = mVN_{\delta F} / A$$

$$\tau_\beta = - I_Z Y_{\delta F} / (mVN_{\delta F} - Y_r N_{\delta F} + N_r Y_{\delta F})$$

$$= - I_Z Y_{\delta F} / [B * \beta_o / (\delta_{SW} / SR)]$$

NORMALIZED LATERAL ACCELERATION RESPONSE:

$$a_Y / a_{Yo} = \frac{[1+(\tau_r + \beta_o/r_o)s + (\beta_o * \tau_\beta / r_o)s^2]}{[1+(2\zeta/\omega_n)s + (1/\omega_n^2)s^2]}$$

ROLL GRADIENT RESPONSE:

$$\phi(s) / a_Y(s) = - [W_S h] / [I_X s^2 - L_P s - L_\phi]$$

SIMULATION RESULTS

VDTV CHARACTERISTICS

FRONT/REAR STEER CONTROL SUBSYSTEMS:
BALLSCREW OR RACK CONTROL
SIMPLE SECOND ORDER RESPONSE:

$$\frac{1}{[\,1 + (2\varsigma\omega_n)s + s^2/\omega_n^2\,]}$$

$\varsigma = 0.707$, $\omega_n/2\pi$ = BANDWIDTH

FRONT AND REAR ASSUMED SAME

RACK TO WHEEL:
IGNORED INERTIA
COMPLIANCE INCLUDED

GAINS TO FRONT AND REAR FROM:
STEERING WHEEL ANGLE
YAW RATE
YAW ACCELERATION
LATERAL ACCELERATION
SIDESLIP ANGLE
SIDESLIP ANGLE RATE
ROLL ANGLE
ROLL RATE
ROLL ACCELERATION

TIRES:

P275/40ZR-17, (DATA FROM GOODYEAR)

TIRE DYNAMICS:

1-FT. RELAXATION LENGTH

CONTINUOUSLY VARIABLE SHOCKS

BASE RATE: 54 LB-SEC/FT

STEEP INITIAL RATE: 415 LB-SEC/FT

NO CONTROL DYNAMICS

(10 ms, - NEGLIGIBLE)

COMMAND PROPORTIONAL TO ROLL RATE

SAME FRONT AND REAR

SPEED CONTROL

FOR EVALUATIONS AT CONSTANT SPEED

DRIVING TORQUE = 5000*(Vc -V)

Vc = SPEED COMMAND

BASELINE VDTV RESPONSE CHARACTERISTICS

UNDERSTEER GRADIENT:
3.31 DEG/G , 3.02 DEG/G ROLL DECOUPLED

ACC. SENSITMTY (75 MPH):l.39 G/l00 DEG SWA

YAW RATE SENSITIVITY: 0.23 (DEG/SEC)/DEG

SIDESLIP GRADIENT: -1.12 DEG/G

ROLL GRADIENT: -4.02 DEG/G

YAW RATE RISE TIME: 0.13 SEC

ACCELERATION RISE TIME: 0.26 SEC

ROLL FREQUENCY: 1.54 hz

ROLL DAMPING RATIO: 0.27

YAW/SIDESLIP NATURAL FREQ. : 1.6 hz

YAW/SIDESLIP DAMPING RATIO: 0.63

ROLL DECOUPLING

OBJECT:

ELIMINATE ROLL TERMS IN LATERAL FORCE AND YAWING MOMENT EQUATIONS:

LET: $\delta_F = \delta_{SW}/SR + K_{f\varphi}\,\varphi + K_{FDP}\,(dp/dt)$

$$\delta_{\cancel{F}} = K_{R\varphi}\,\varphi + K_{RDP}\,(dp/dt)$$

ROLL ANGLE TERMS:

$$Y_\varphi + Y_{\delta F}\,K_{f\varphi} + Y_{\delta R}\,K_{r\varphi} = 0$$

$$N_\varphi + N_{\delta F}\,K_{f\varphi} + N_{\delta R}\,K_{r\varphi} = 0$$

ROLL ACCELERATION TERMS:

$$m_S\,h - Y_{\delta F}\,K_{FDP} + Y_{\delta R}\,K_{RDP} = 0$$

$$I_{XZ} - N_{\delta F}\,K_{FDP} + N_{\delta R}\,K_{RDP} = 0$$

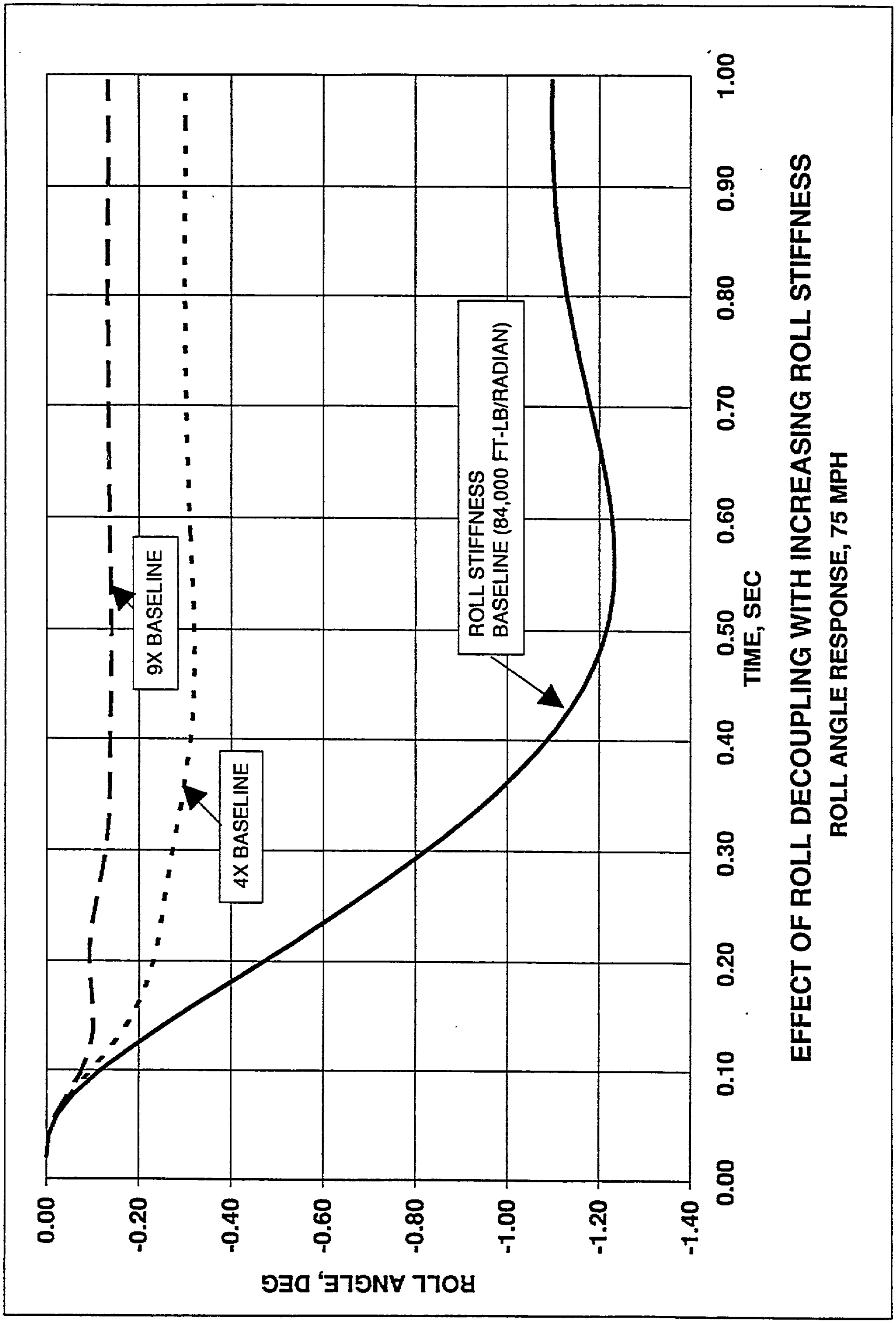
SOLVE FOR FEEDBACK GAINS: $K_{f\varphi}$, $K_{r\varphi}$,K_{FDP} , K_{RDP}

ADVANTAGES:

- **LEAVES YAW SIDESLIP RESPONSE SECOND ORDER**
- **SIMPLE TO ANALYZE**
- **FACILITATES CALCULATION OF GAINS TO CHANGE SPECIFIC METRICS**

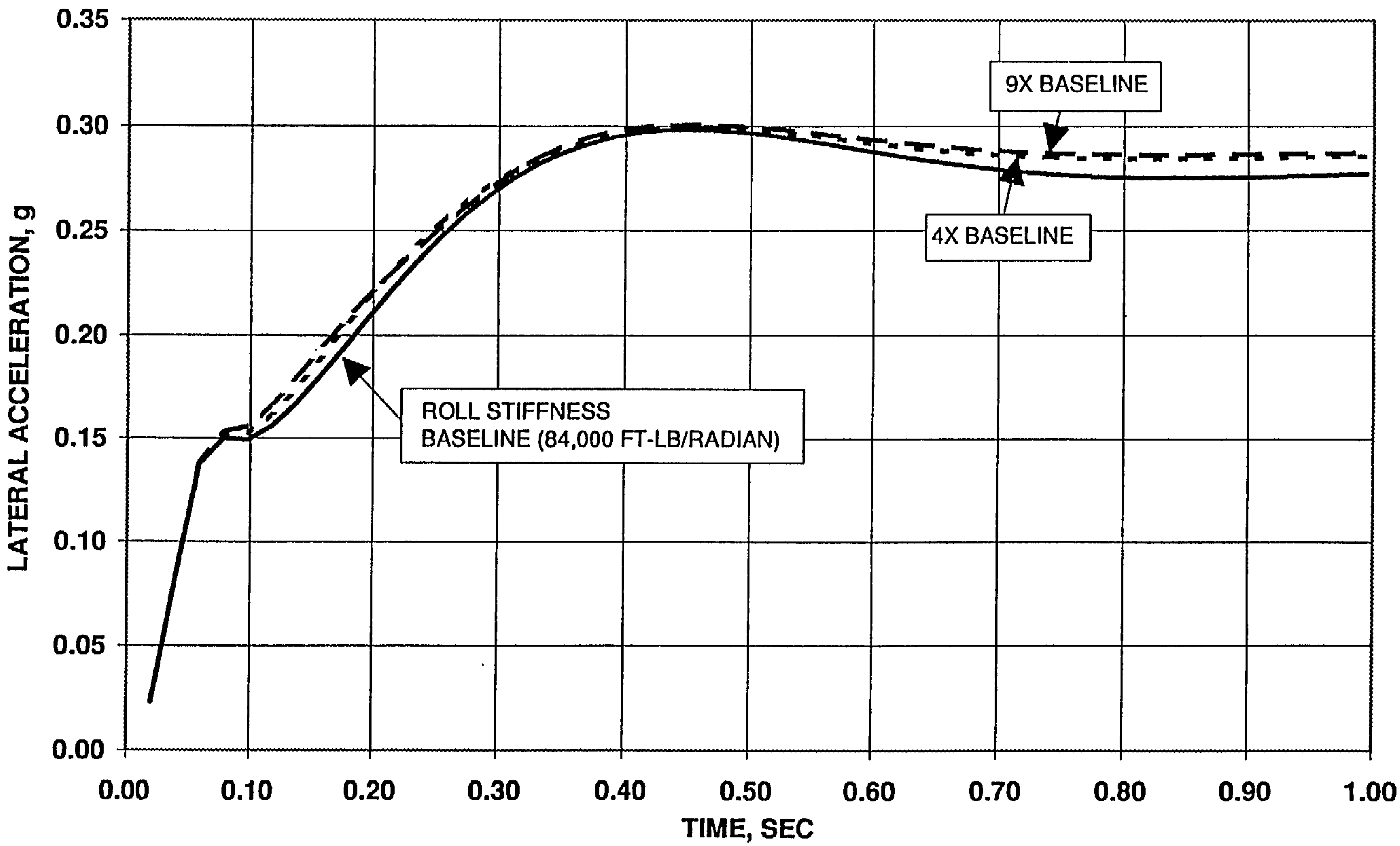
GAINS FOR ROLL DECOUPLING:

- **ROLL ANGLE:**
  - **FRONT: 0.0657, REAR: -.0219**
- **ROLL ACCELERATION:**
  - **FRONT: .00387, REAR: .00155**



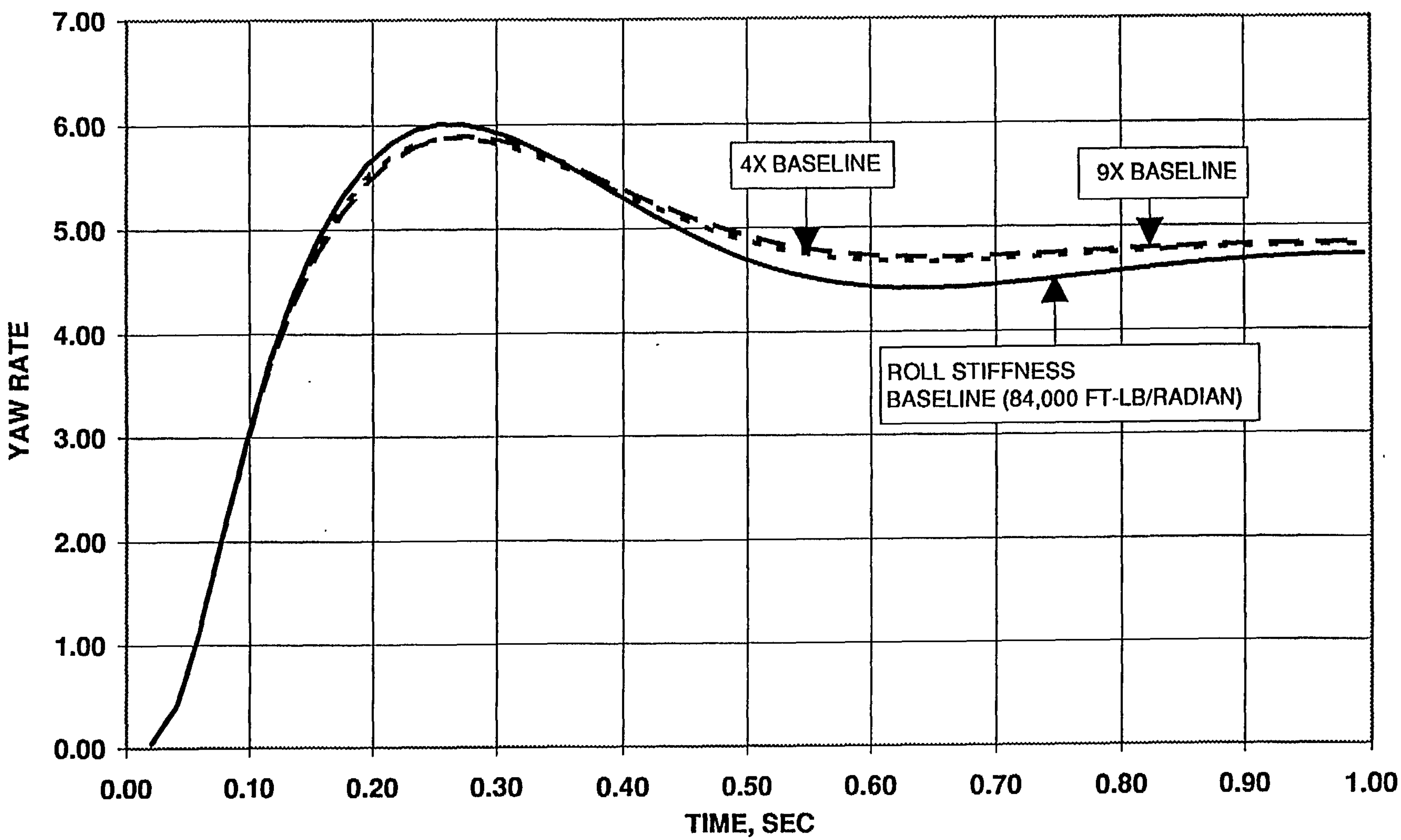
EFFECT OF ROLL DECOUPLING WITH INCREASING ROLL STIFFNESS
ROLL ANGLE RESPONSE, 75 MPH

V15.XLS



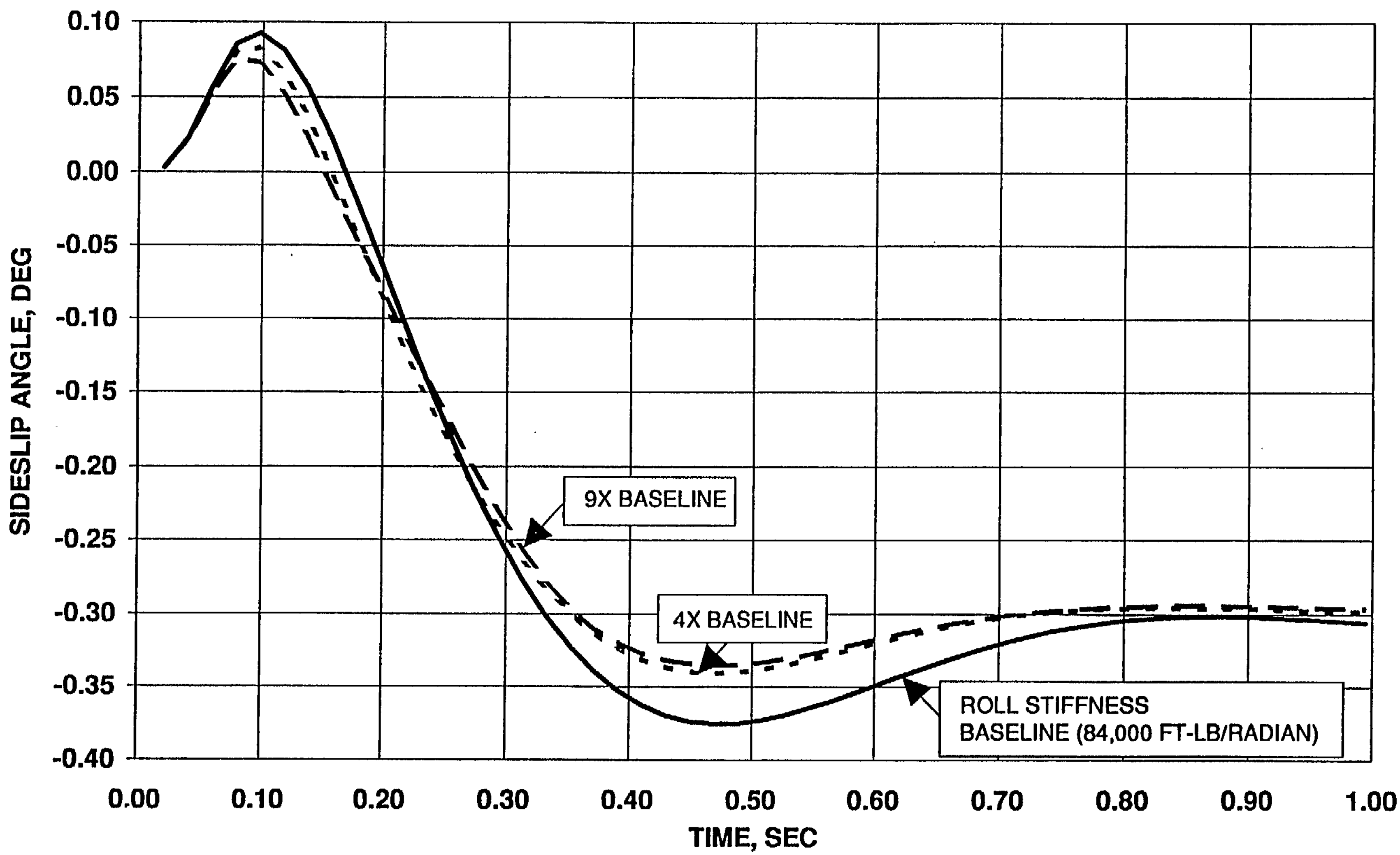
EFFECT OF ROLL DECOUPLING WITH INCREASING ROLL STIFFNESS
LATERAL ACCELERATION RESPONSE, 75 MPH

V15.XLS



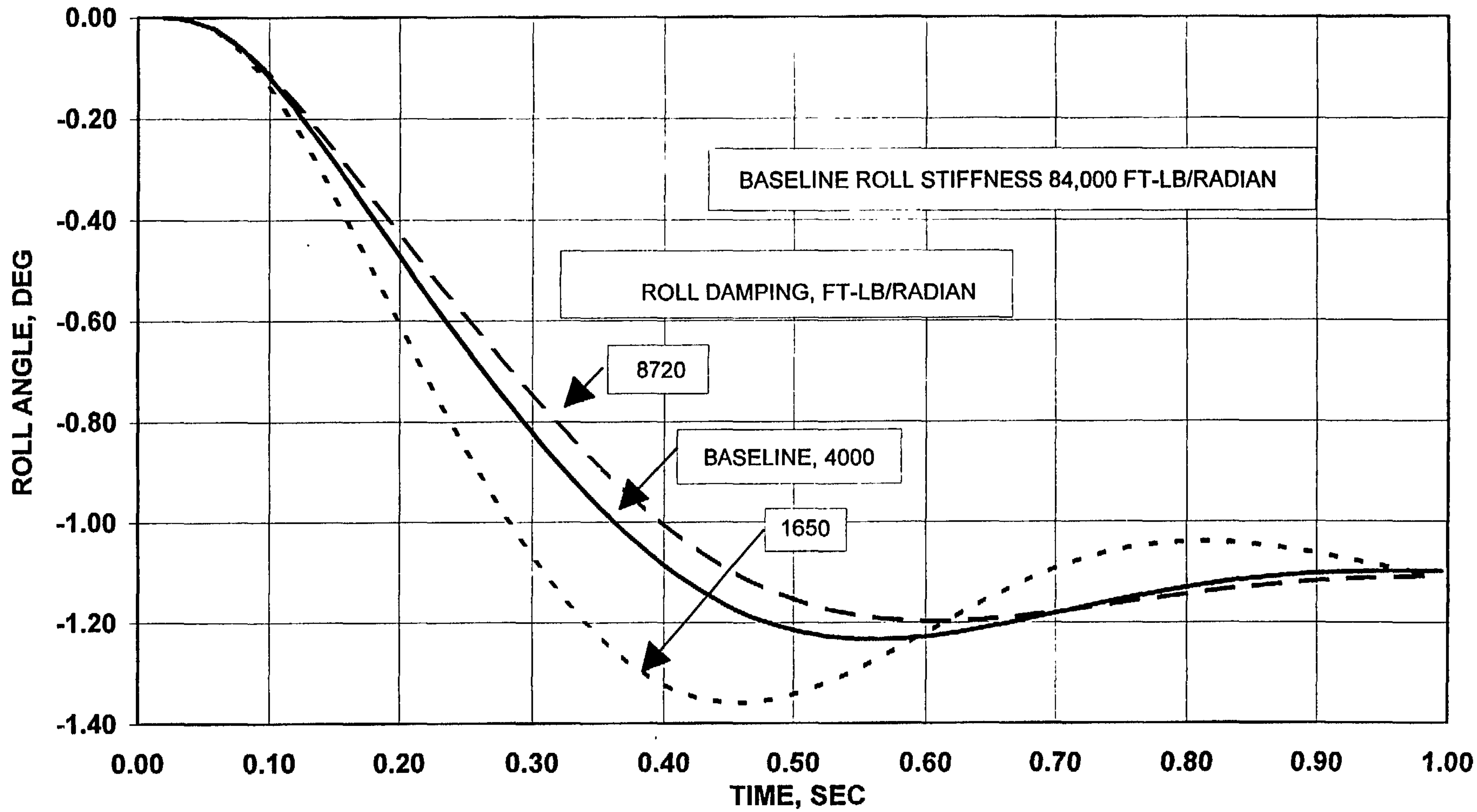
EFFECT OF ROLL DECOUPLING WITH INCREASING ROLL STIFFNESS
YAW RATE RESPONSE, 75 MPH

V15.XLS



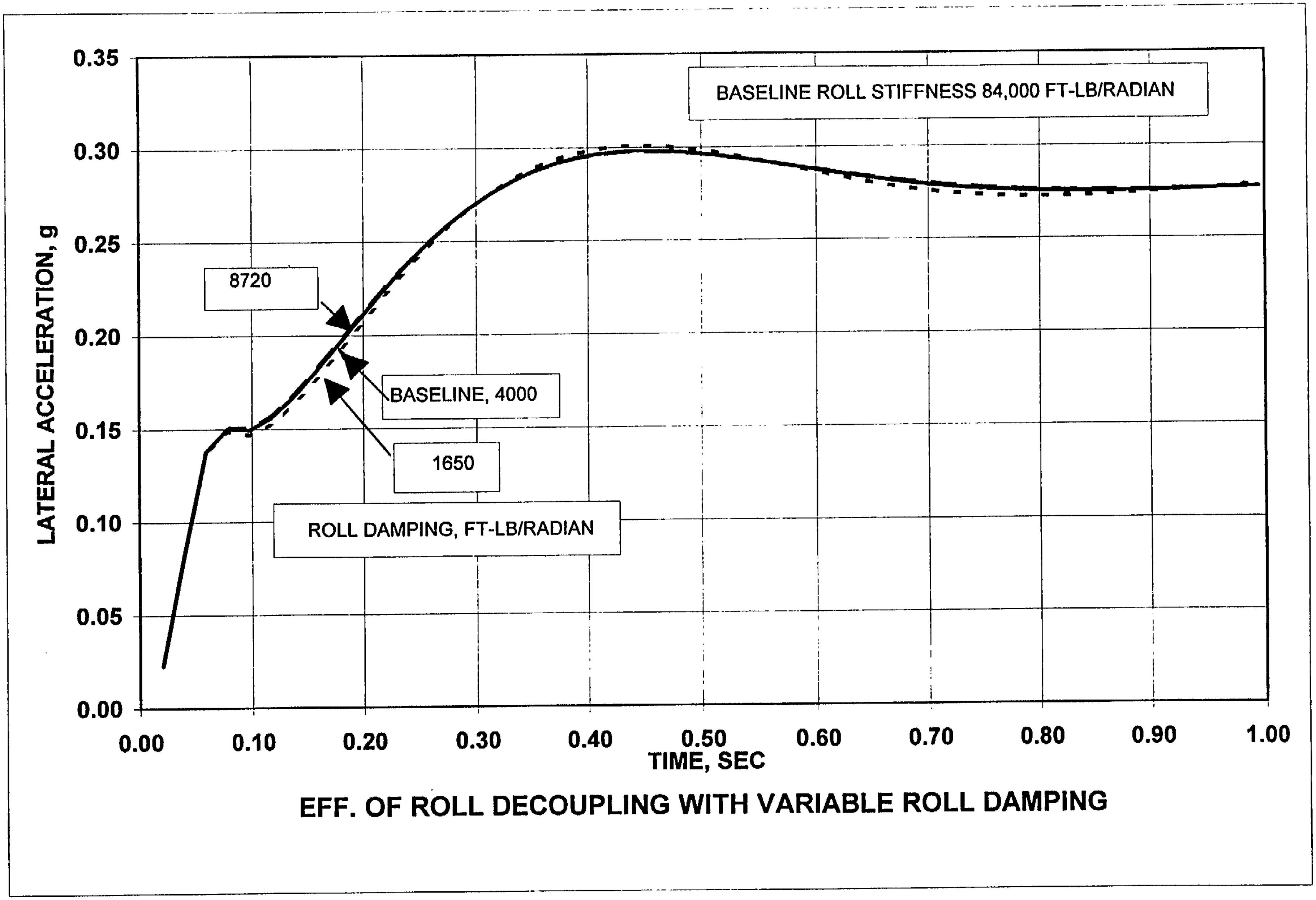
EFFECT OF ROLL DECOUPLING WITH INCREASING ROLL STIFFNESS
SIDESLIP ANGLE RESPONSE, 75 MPH

V15.XLS



EFF. OF ROLL DECOUPLING WITH VARIABLE ROLL DAMPING

V15.XLS



BASELINE ROLL STIFFNESS 84,000 FT-LB/RADIAN
8720
BASELINE, 4000
1650
ROLL DAMPING, FT-LB/RADIAN
LATERAL ACCELERATION, g
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0.00
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80
0.90
1.00
TIME, SEC
EFF. OF ROLL DECOUPLING WITH VARIABLE ROLL DAMPING

V15.XLS

SIDESLIP GRADIENT

OBJECTIVE:

VARY SIDESLIP GRADIENT (β/a_Y) WHILE HOLDING THE UNDERSTEER GRADIENT CONSTANT.

ELIMINATE SIDESLIP TERM FROM YAWING MOMENT EQUATION,LEAVING:

$$I_Z\,(dr/dt) = N_r'\,r + N_{\delta F}\,(\delta_{SW} / SR)$$

THIS EFFECTIVELY DECOUPLES SIDESLIP FROM YAW RATE SO THAT SIDESLIP CAN BE VARIED BY CHANGING TERMS IN THE LATERAL FORCE EQUATION.

$$mV[(d\beta/dt) + r\,] = Y_\beta'\,\beta + Y_r'\,r + Y_{\delta F}\,(\delta_{SW} / SR)$$

IN THE STEADY STATE:

$$(mV - Y_r')\,r = Y_\beta'\,\beta + Y_{\delta F}\,(\delta_{SW} / SR)$$

$$0 = N_r'\,r + N_{\delta F}\,(\delta_{SW} / SR)$$

SO THAT: $r = -\,(N_{\delta F} / N_r')*(\delta_{SW} / SR)$

AND: $\beta/\delta_{SW} = -\,[(\,Y_{\delta F}*N_r' - N_{\delta F}*Y_r'\,) + mVN_{\delta F}\,] \,/\, [Y_\beta'\,N_r']$

SPEED: 75 MPH, ROLL DECOUPLED

GAINS , ETC.:

K_{fr} SEC	K_{rr} SEC	$K_{f\beta}$	$K_{r\beta}$	U/G DEG/G	a_Y G	β/δ_{SW}	β/a_Y DEG/G
0	0	0	0	3.02	.286	-.015	-1.05
-.2	-.0343	0.4	.760	3.43	.262	-.092	-7.03
+.2	-.1249	-5.0	-1.396	3.32	.268	.005	0.41
+.2	-.1249	0.6	.840	3.26	.271	.082	6.01

UNDERSTEER GRADIENT

GAIN SELECTION:

1) HOLD $(Y_\beta' N_{\delta F} - N_\beta' Y_{\delta F})$ CONSTANT

REQUIRES: $K_{r\beta} = 0$

2) HOLD $(N_\beta' Y_r' - Y_\beta' N_r')$ CONSTANT

REQUIRES:

$$K_{fr} = \frac{(N_{\delta F} Y_r - Y_{\delta F} N_r)}{(N_{\delta F} Y_\beta - Y_{\delta F} N_\beta)} * K_{f\beta}$$

$K_{Rr} = 0$

SIMULATION RUNS:

360 DEG/SEC STEERING WHEEL RATE

STEERING WHEEL ANGLE VARIED WITH SPEED
TO KEEP LAT. ACC. = 0.25G

STEER CONTROL BANDWIDTH: 20 hz

EFFECT OF SPEED

UNDERSTEER GRADIENT: -4 DEG/G

FILE	SPEED MPH	$K_{f\beta}$	K_{fr} SEC	U/G DEG/G	δ_{SW} DEG	a_Y G
V32A	20	-4.0	0.746	-4.7	57.0	.250
V32B	25	-4.0	0.597	-4.8	29.5	.250
V32C	30	-4.0	0.497	-4.7	14.5	.247
V32D	35	-4.0	0.426	-4.6	6.3	.253
V32E	40	-4.0	0.373	-4.6	2.2	.254

NOTE: CRITICAL SPEED ≈ 40 MPH
UNSTABLE ABOVE THIS SPEED

UNDERSTEER GRADIENT = +13.2 DEG/G

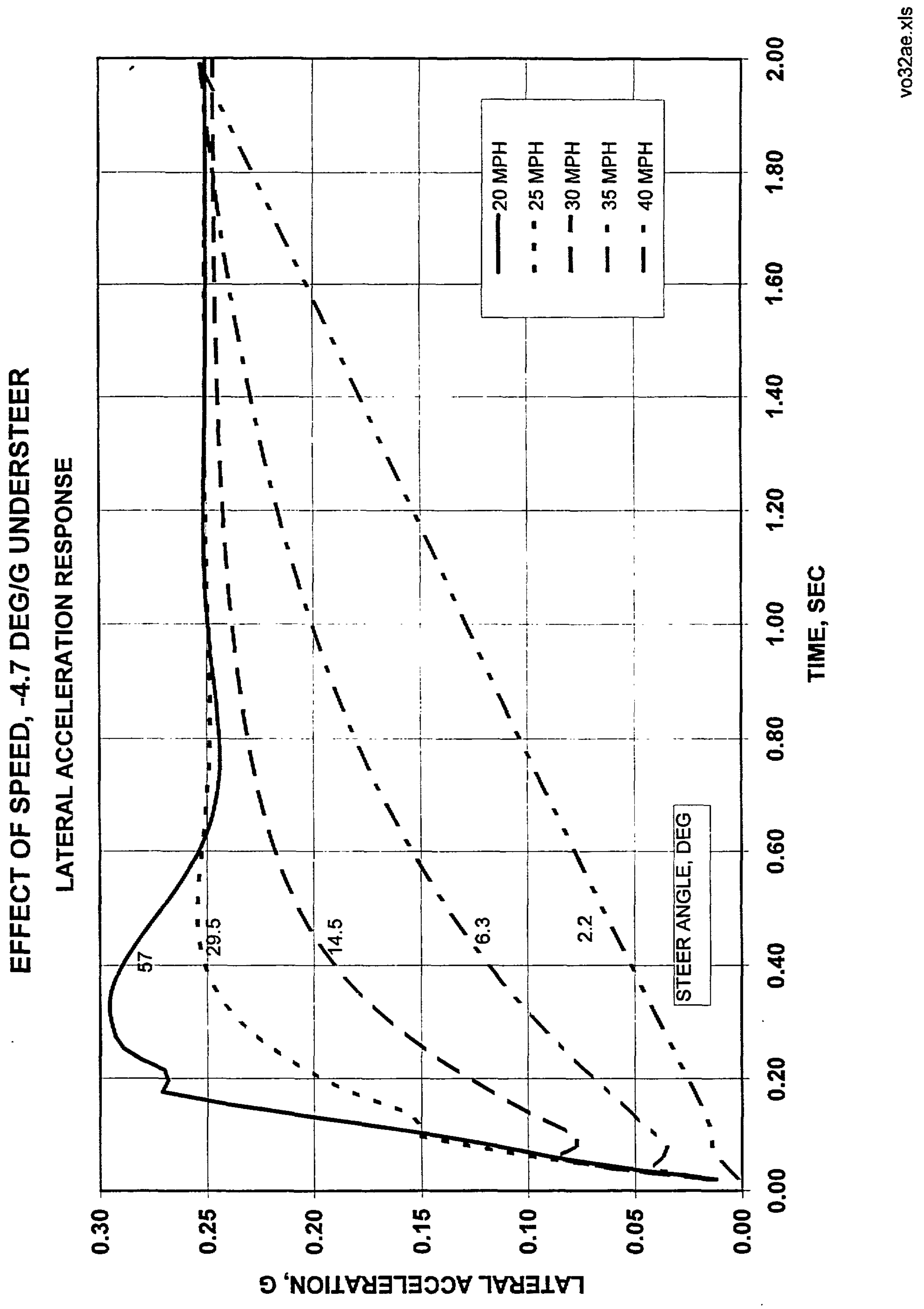
FILE	SPEED MPH	$K_{f\beta}$	K_{fr} SEC	U/G DEG/G	δ_{SW} DEG	a_Y G
V33A	20	-5.15	-0.960	13.23	134.0	.260
V33B	40	-5.15	-0.480	13.22	75.0	.261
V33C	60	-5.15	-0.320	13.20	64.0	.261
V33D	80	-5.15	-0.240	13.19	59.4	.259

EFFECT OF STEER AMPLITUDE:

TIME HISTORIES FOR:

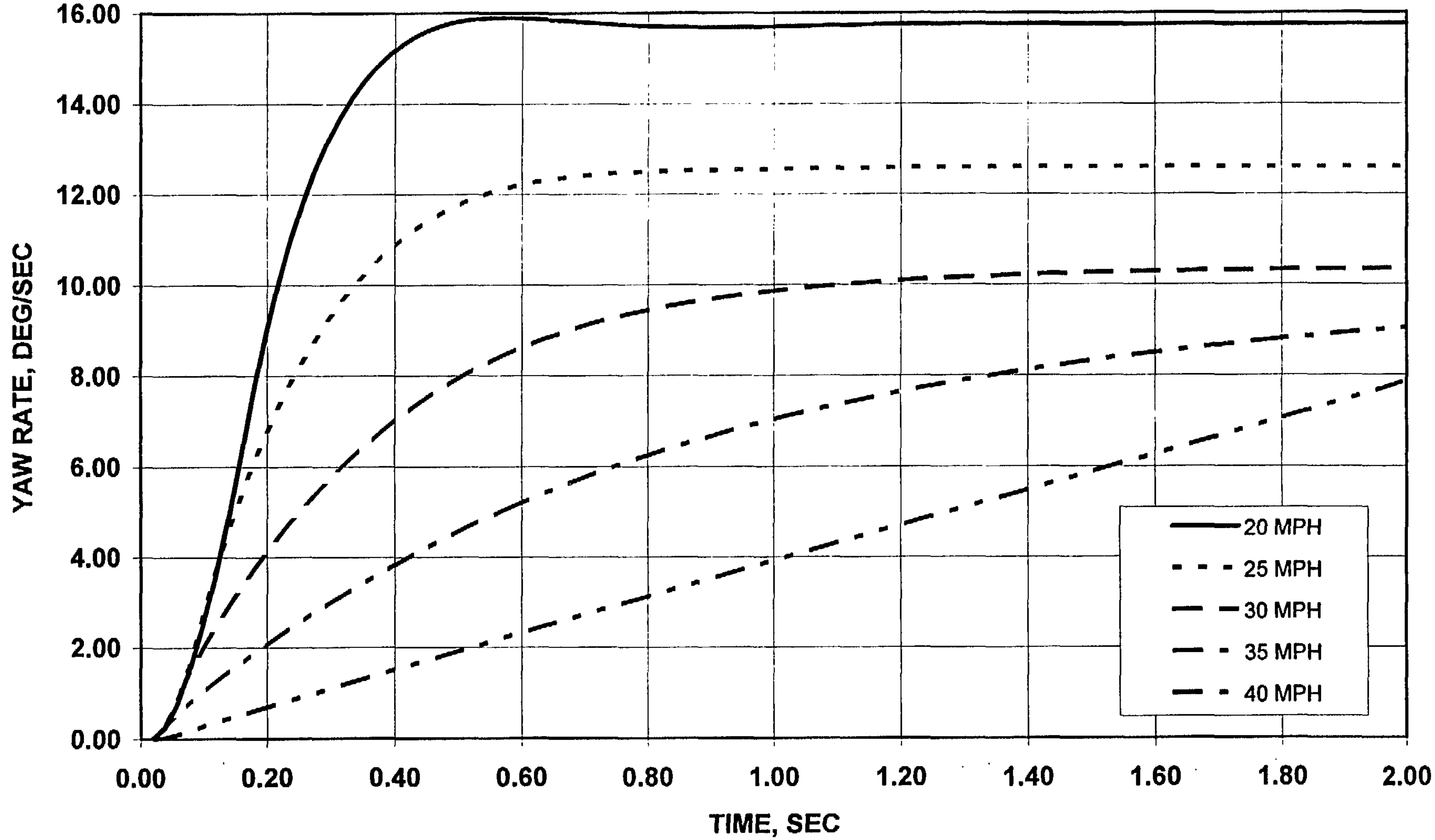
50 KM/HR, U/G = -4.6 DEG/G FOR $a_Y < 0.3$G

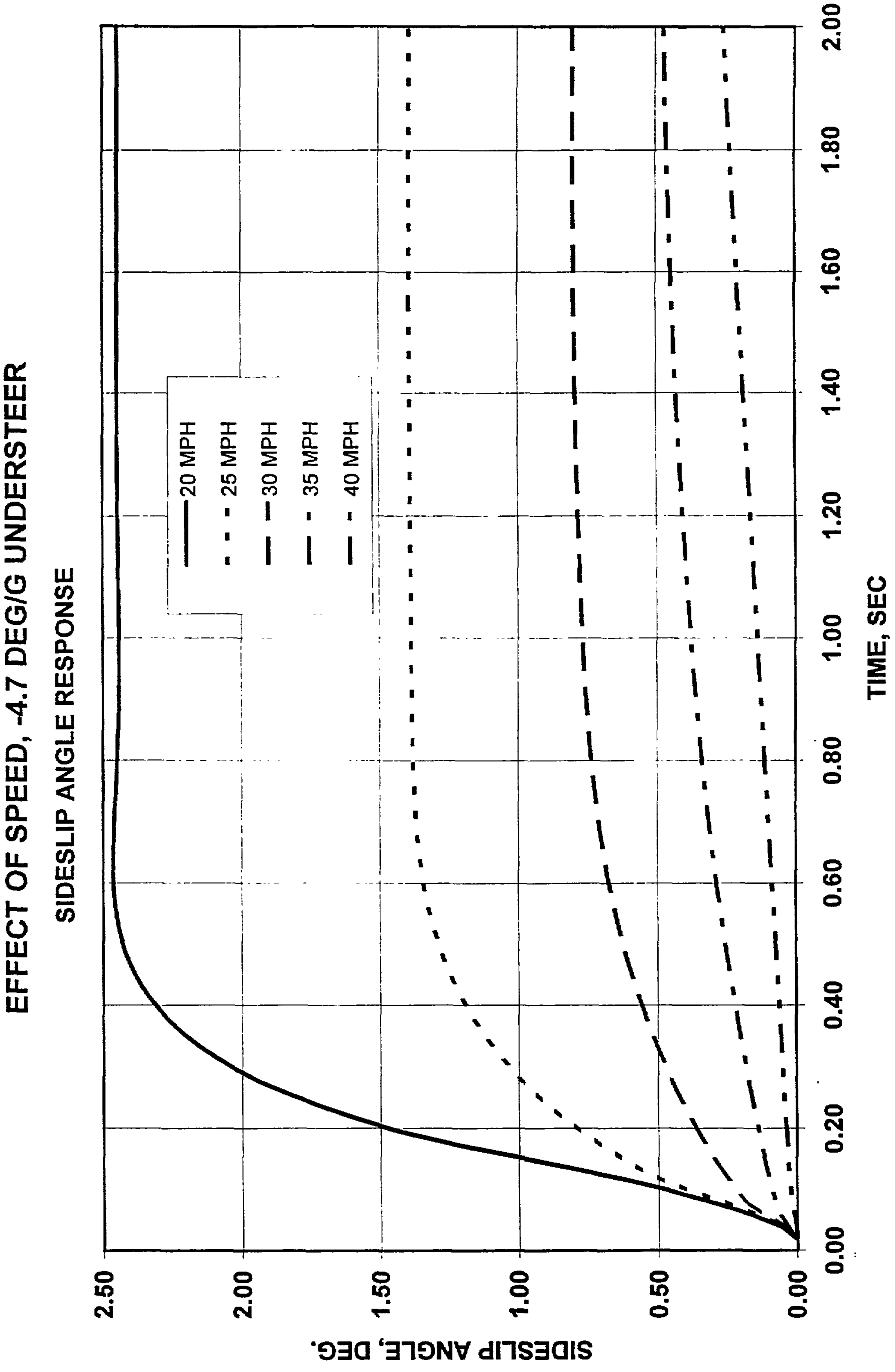
80 KM/HR, U/G = +13.2 DEG/G FOR $a_Y < 0.3$G


EFFECT OF SPEED, -4.7 DEG/G UNDERSTEER
LATERAL ACCELERATION RESPONSE
LATERAL ACCELERATION, G
TIME, SEC
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.20
0.40
0.60
0.80
1.00
1.20
1.40
1.60
1.80
2.00
20 MPH
25 MPH
30 MPH
35 MPH
40 MPH
57
29.5
14.5
6.3
2.2
STEER ANGLE, DEG
vo32ae.xls

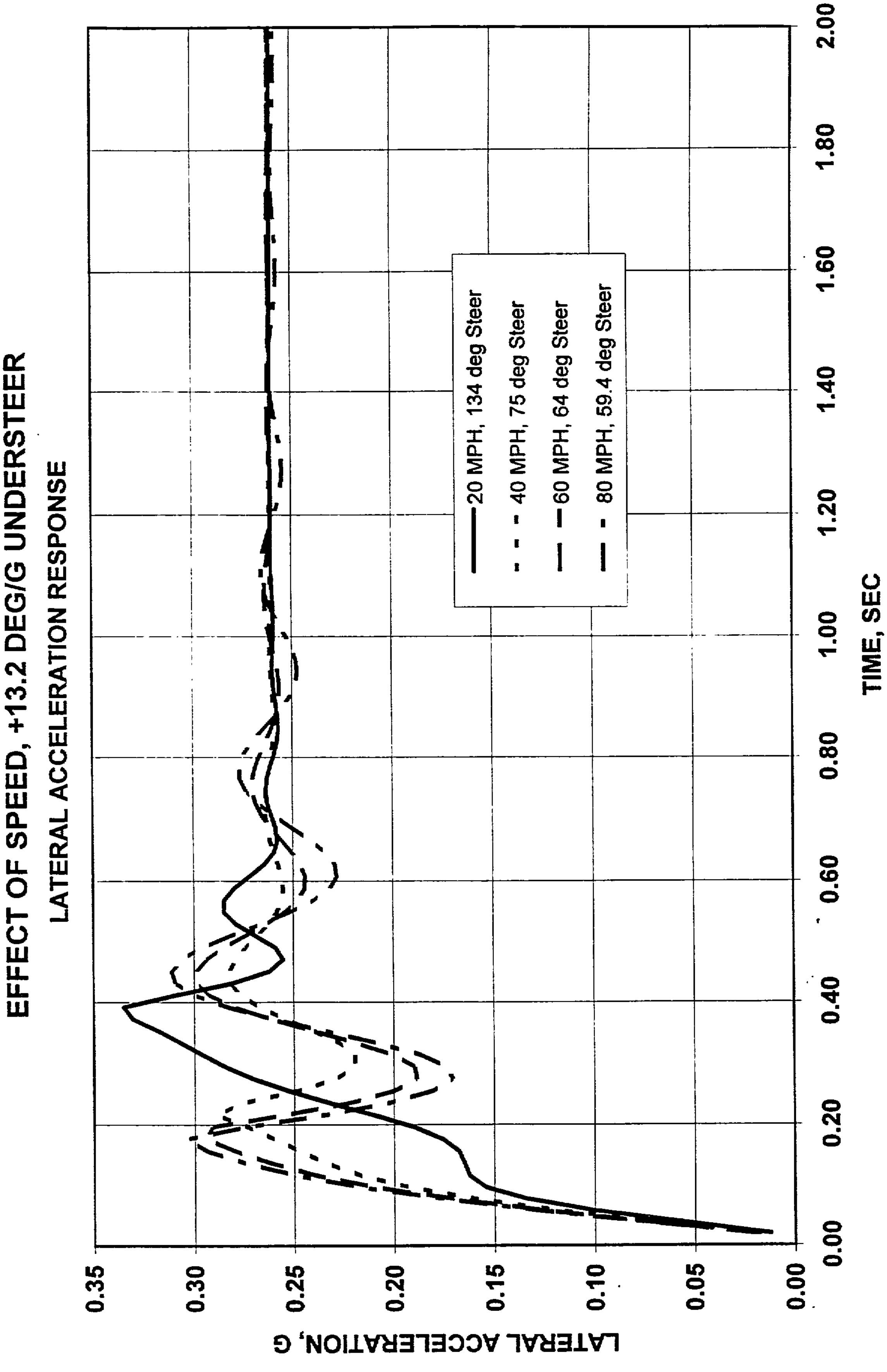
EFFECT OF SPEED, -4.7 DEG/G UNDERSTEER

YAW RATE RESPONSE

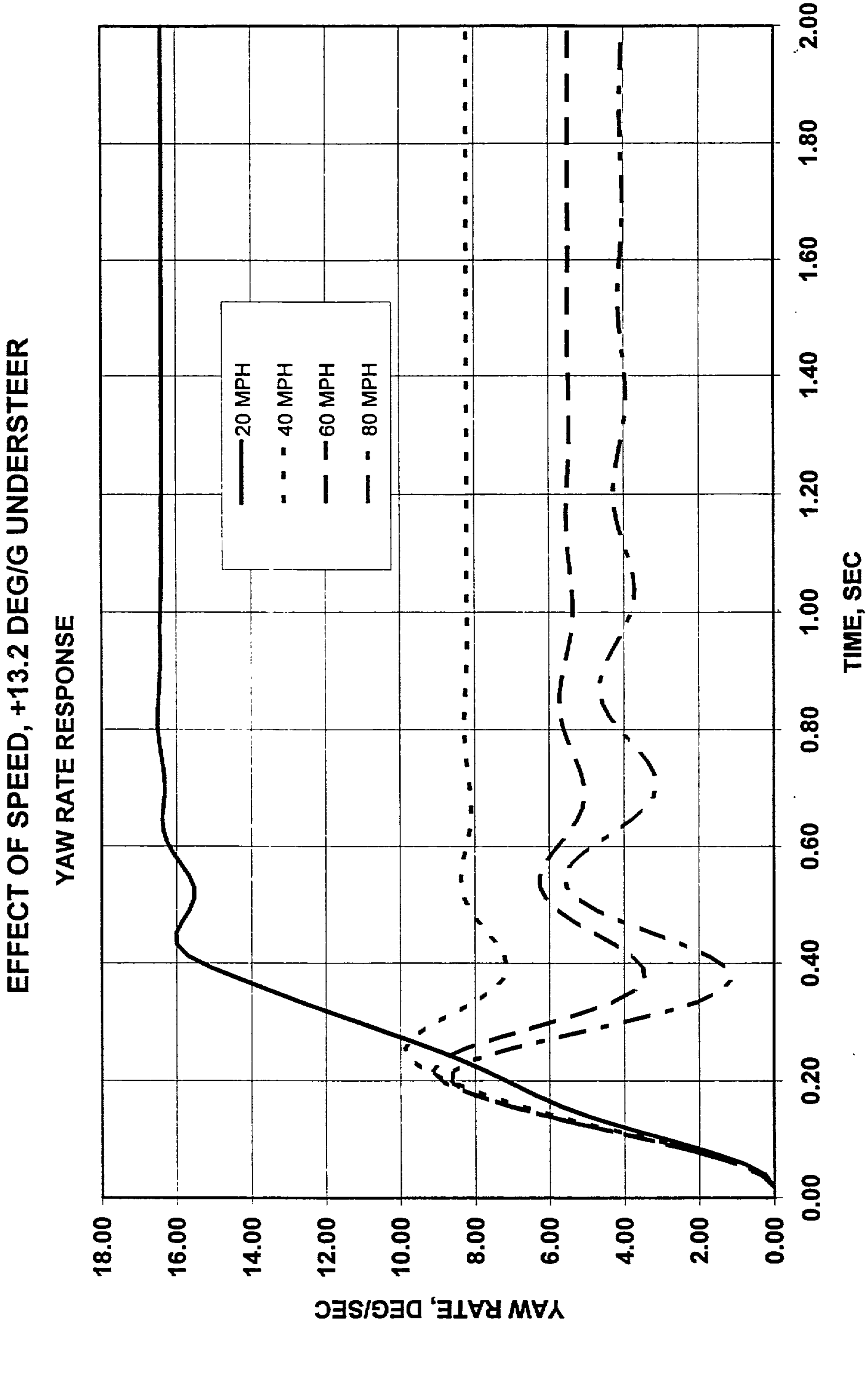



EFFECT OF SPEED, -4.7 DEG/G UNDERSTEER
SIDESLIP ANGLE RESPONSE
20 MPH
25 MPH
30 MPH
35 MPH
40 MPH
SIDESLIP ANGLE, DEG.
2.50
2.00
1.50
1.00
0.50
0.00
TIME, SEC
0.00
0.20
0.40
0.60
0.80
1.00
1.20
1.40
1.60
1.80
2.00

V33AD.YLS



EFFECT OF SPEED, +13.2 DEG/G UNDERSTEER
LATERAL ACCELERATION RESPONSE
LATERAL ACCELERATION, G
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
TIME, SEC
0.00
0.20
0.40
0.60
0.80
1.00
1.20
1.40
1.60
1.80
2.00
20 MPH, 134 deg Steer
40 MPH, 75 deg Steer
60 MPH, 64 deg Steer
80 MPH, 59.4 deg Steer



EFFECT OF SPEED, +13.2 DEG/G UNDERSTEER
YAW RATE RESPONSE
20 MPH
40 MPH
60 MPH
80 MPH
YAW RATE, DEG/SEC
18.00
16.00
14.00
12.00
10.00
8.00
6.00
4.00
2.00
0.00
TIME, SEC
0.00
0.20
0.40
0.60
0.80
1.00
1.20
1.40
1.60
1.80
2.00

POTENTIAL VDTV USES:

0 INVESTIGATION OF "EXTERNAL SUBSYSTEMS
E.G., AHS
- USE SPECIFIC CONFIGURATIONS
SMALL, MEDIUM AND LARGE CAR EMULATION

0 RESEARCH ON HANDLING METRICS
- CONTINUOUSLY VARIABLE DYNAMICS

0 EMULATION OF SPECIFIC VEHICLES
- MATCH METRICS
- MATCH STABILITY DERIVATIVES
- MODEL FOLLOWING

VDTV OPERATION

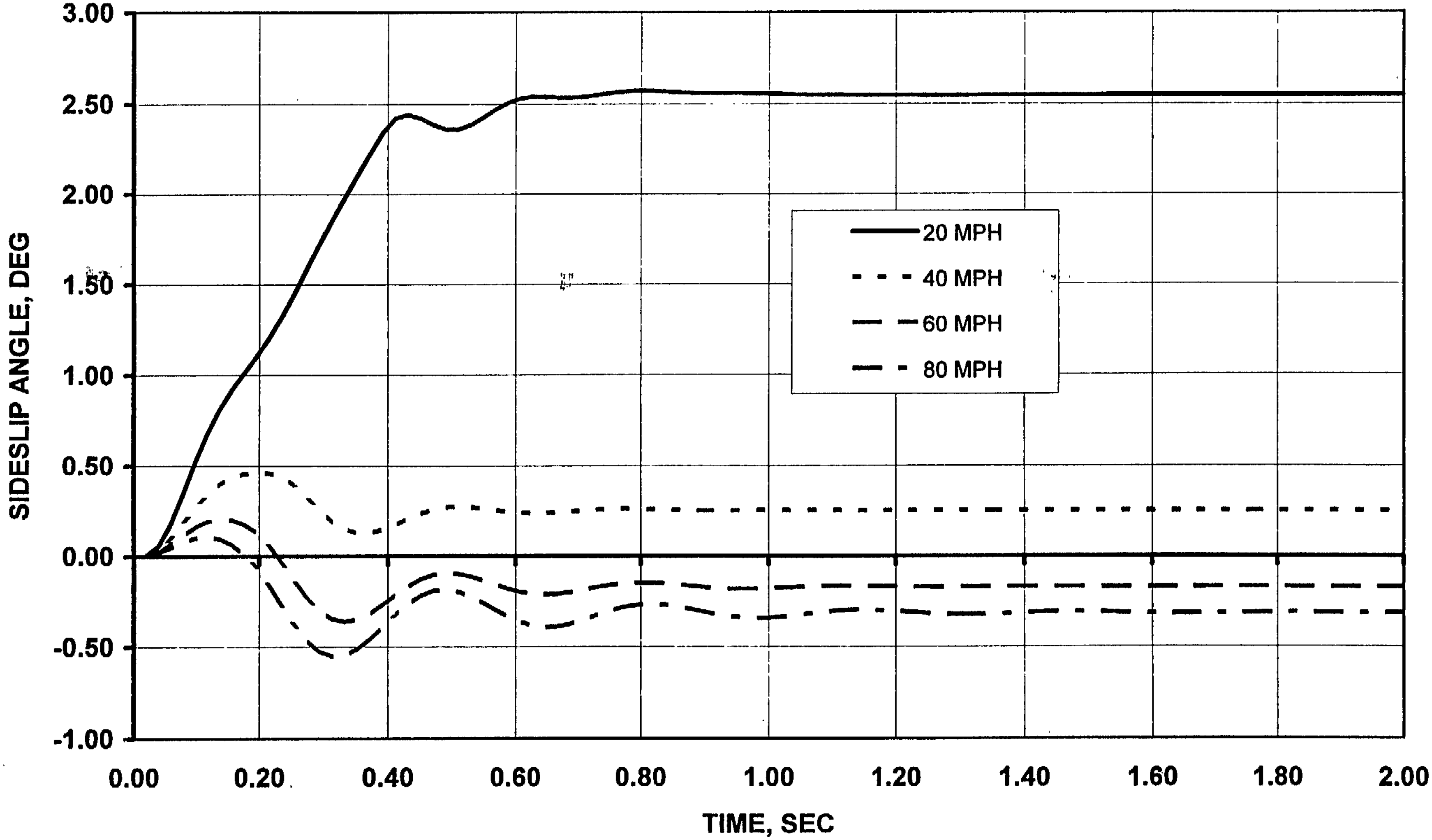
0 EMULATION OR RESEARCH AT SPECIFIC SPEED

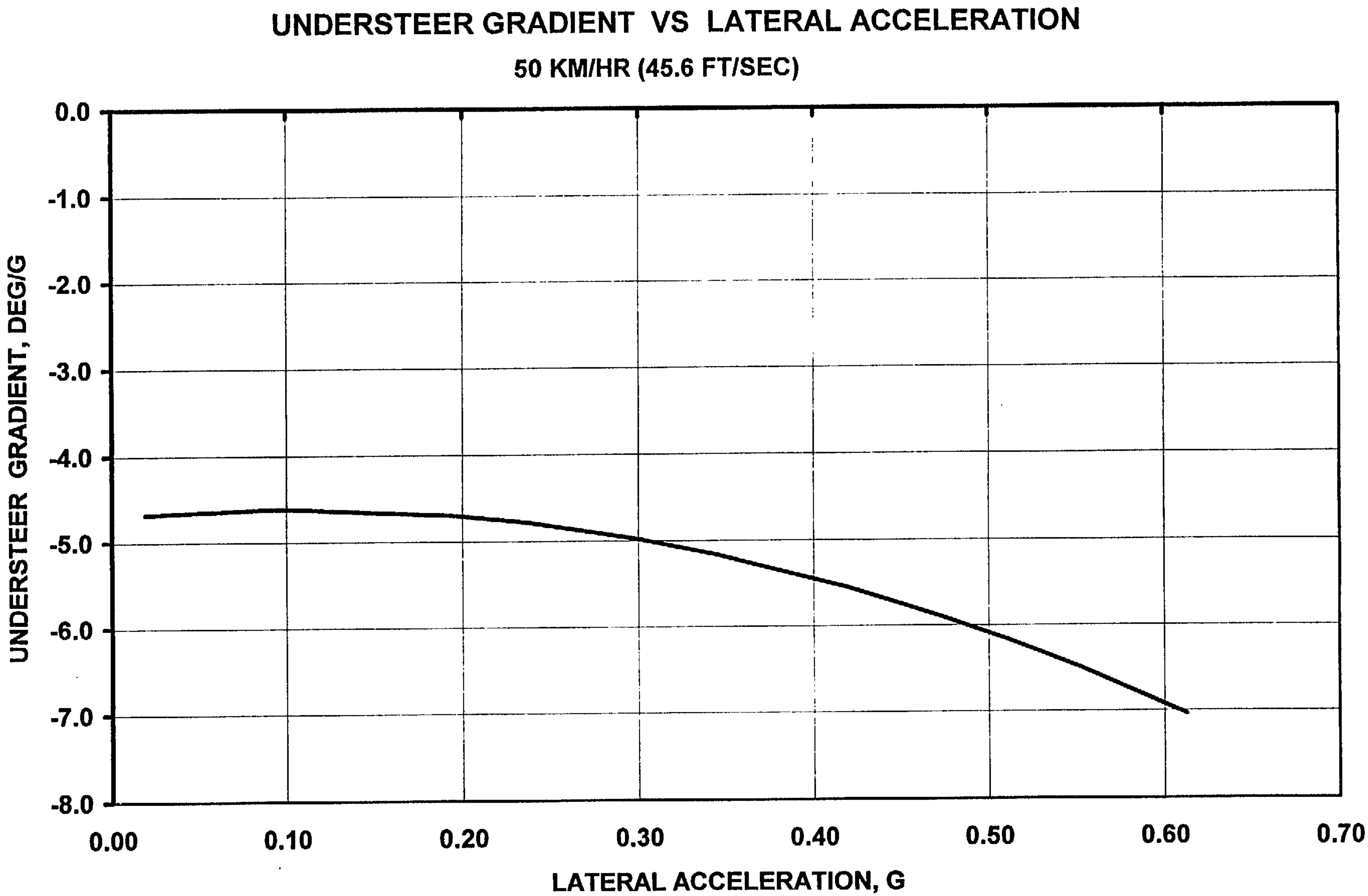
0 DRIVE OVER THE SPEED RANGE
- PROGRAM GAINS WITH SPEED

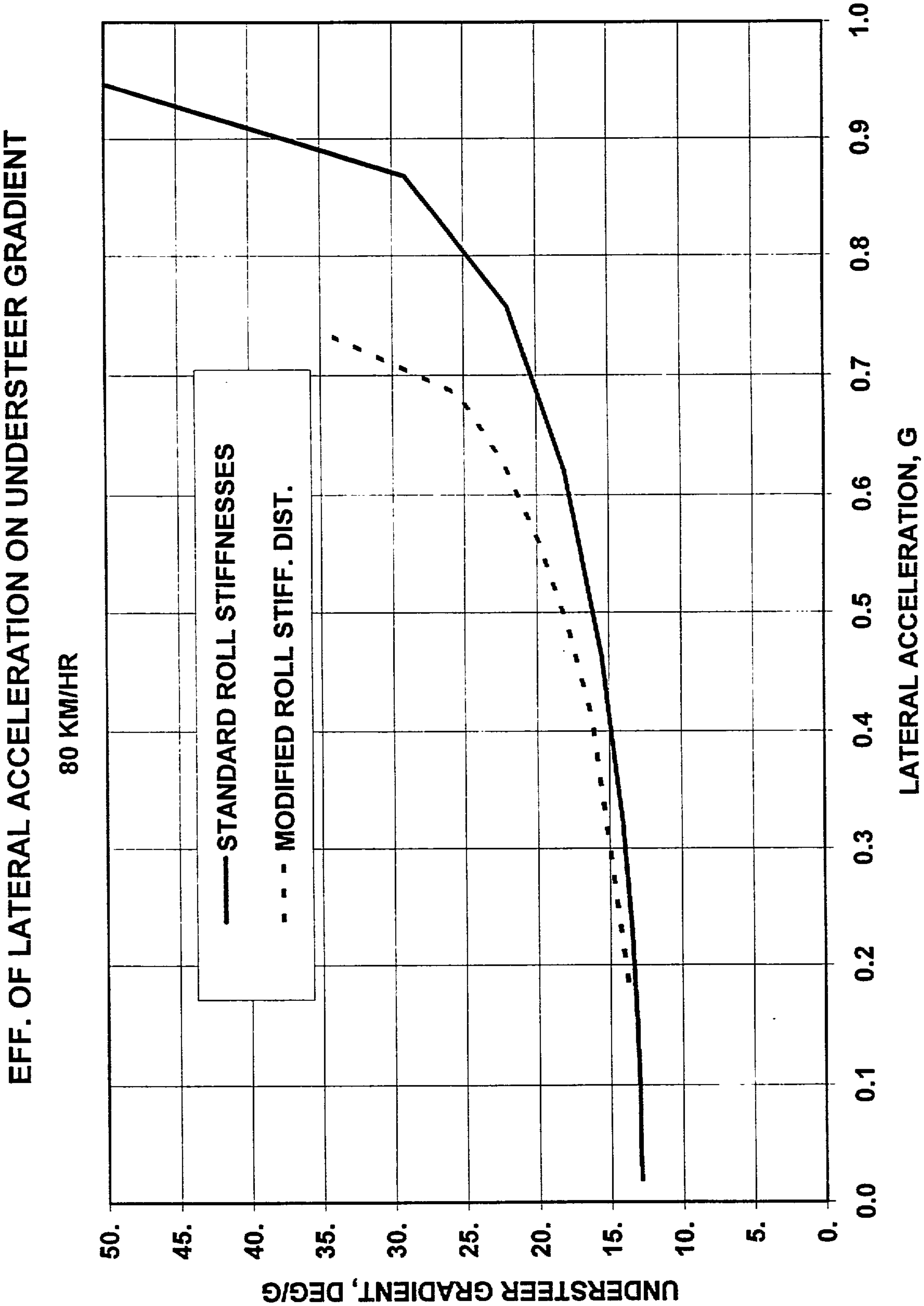
0 RANGE OF LATERAL ACCELERATIONS
- ON-CENTER (NOT IN RFP): < 0.1G
- LOW ACCELERATION (LINEAR RANGE): < 0.3G
- MID RANGE: 0.3G < A_Y < 0.6G
- LIMIT MANEUVERS: 0.6G < A_Y < MAX. LATERAL

EFFECT OF SPEED, +13.2 DEG/G UNDERSTEER

SIDESLIP ANGLE RESPONSE




UNDERSTEER GRADIENT VS LATERAL ACCELERATION
50 KM/HR (45.6 FT/SEC)
UNDERSTEER GRADIENT, DEG/G
0.0
-1.0
-2.0
-3.0
-4.0
-5.0
-6.0
-7.0
-8.0
0.00
0.10
0.20
0.30
0.40
0.50
0.60
0.70
LATERAL ACCELERATION, G


EFF. OF LATERAL ACCELERATION ON UNDERSTEER GRADIENT
80 KM/HR
STANDARD ROLL STIFFNESSES
MODIFIED ROLL STIFF. DIST.
UNDERSTEER GRADIENT, DEG/G
LATERAL ACCELERATION, G
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
0.
5.
10.
15.
20.
25.
30.
35.
40.
45.
50.

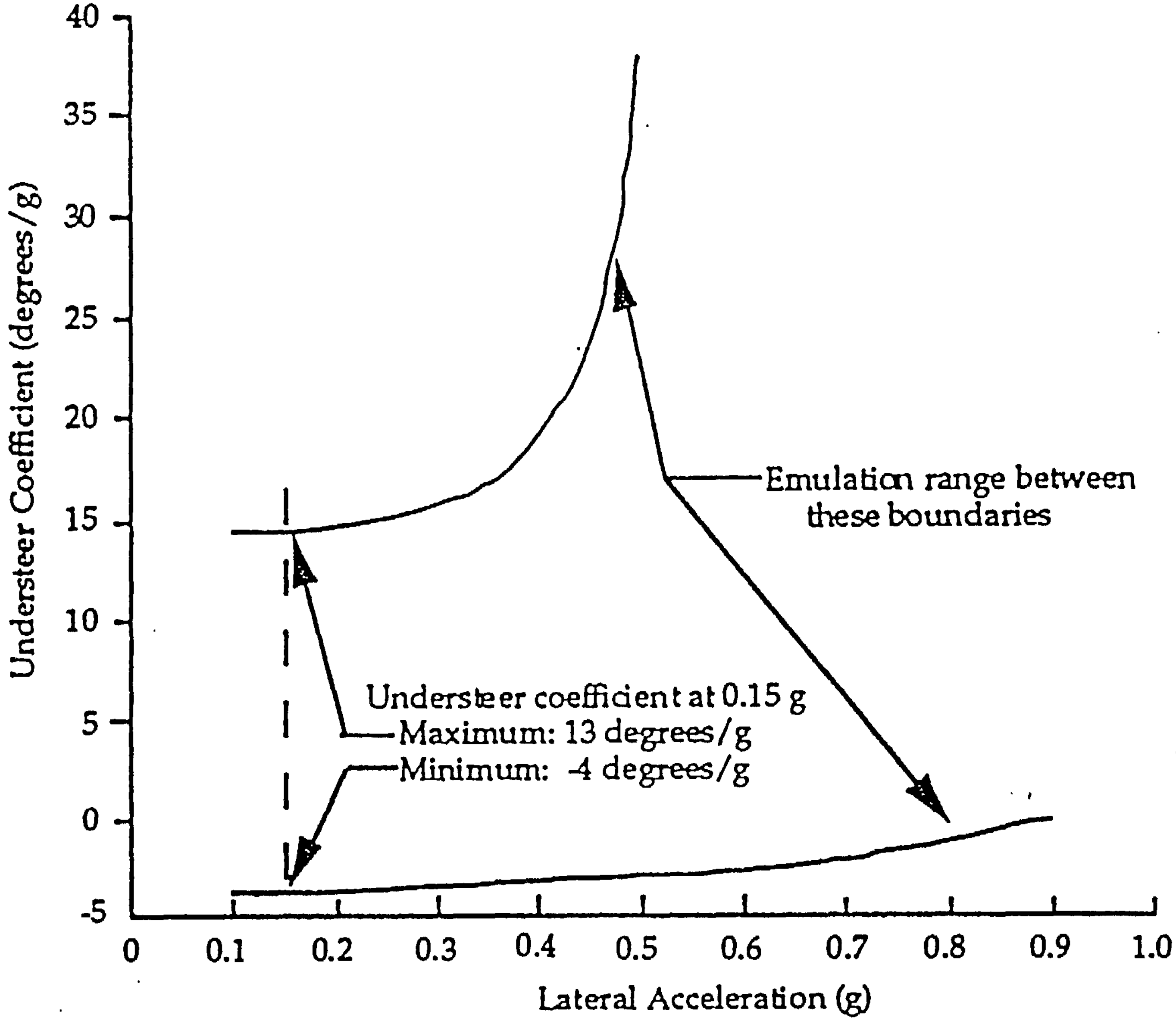


Figure 3-5. Understeer Coefficient Emulation

YAW RATE OVERSHOOT AND TIME TO PEAK

APPROACH:

$$2\zeta\,\omega_n = -\,(N_r / I_Z + Y_\beta / mV)$$

REDUCE DAMPING BY INCREASING I_Z,

$$I_Z' = I_Z + N_{\delta F} K_{FDr} + N_{\delta R} K_{FDr}$$

BUT DON'T INTRODUCE AN EXTRANEOUS (dr/dt) TERM IN THE LATERAL FORCE EQUATION.

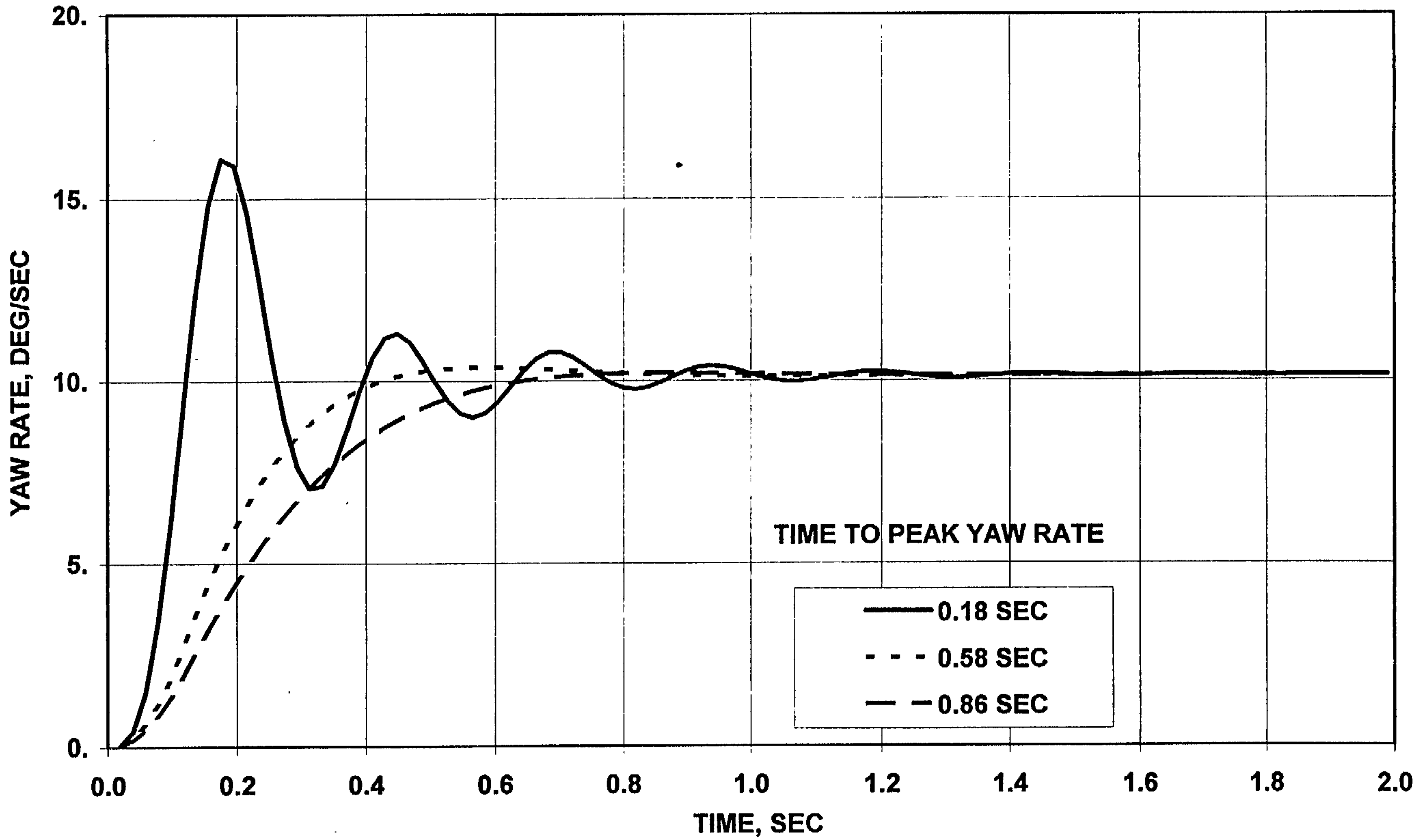
REQUIRES:

$$Y_{\delta F} K_{FDr} + Y_{\delta R} K_{RDr} = 0$$

$$K_{RDr} = -\,(Y_{\delta F} / Y_{\delta R})^{*}\, K_{FDr}$$

UNDERSTEER GRADIENT: 3.2 DEG/G
50 MPH, 0.4G STEADY STATE LAT. ACC.

K_{FDr} SEC	K_{RDr} SEC	I_Z' FT-LB-SEC^2	PERCENT OVERSHOOT	TIME TO PEAK
0	0	2199	7.5	0.31
.0075	-.00511	131	58.	0.18
-.010	.00682	4956	2.3	0.58
-.020	.01363	7712	0.8	0.86



VARYING TIME TO PEAK YAW RATE RESPONSE
50 MPH, 0.4G STEADY STATE LAT. ACC.

VO3840.XLS

LATERAL ACCELERATION RISE TIME

USE ($d\beta/dt$) AND (dr/dt) FEEDBACK GAINS

REQUIRE:

$$Y_{\delta F} K_{FDr} + Y_{\delta R} K_{RDr} = 0$$

(NO EXTRANEOUS (dr/dt) TERM IN LATERAL FORCE EQUATON)

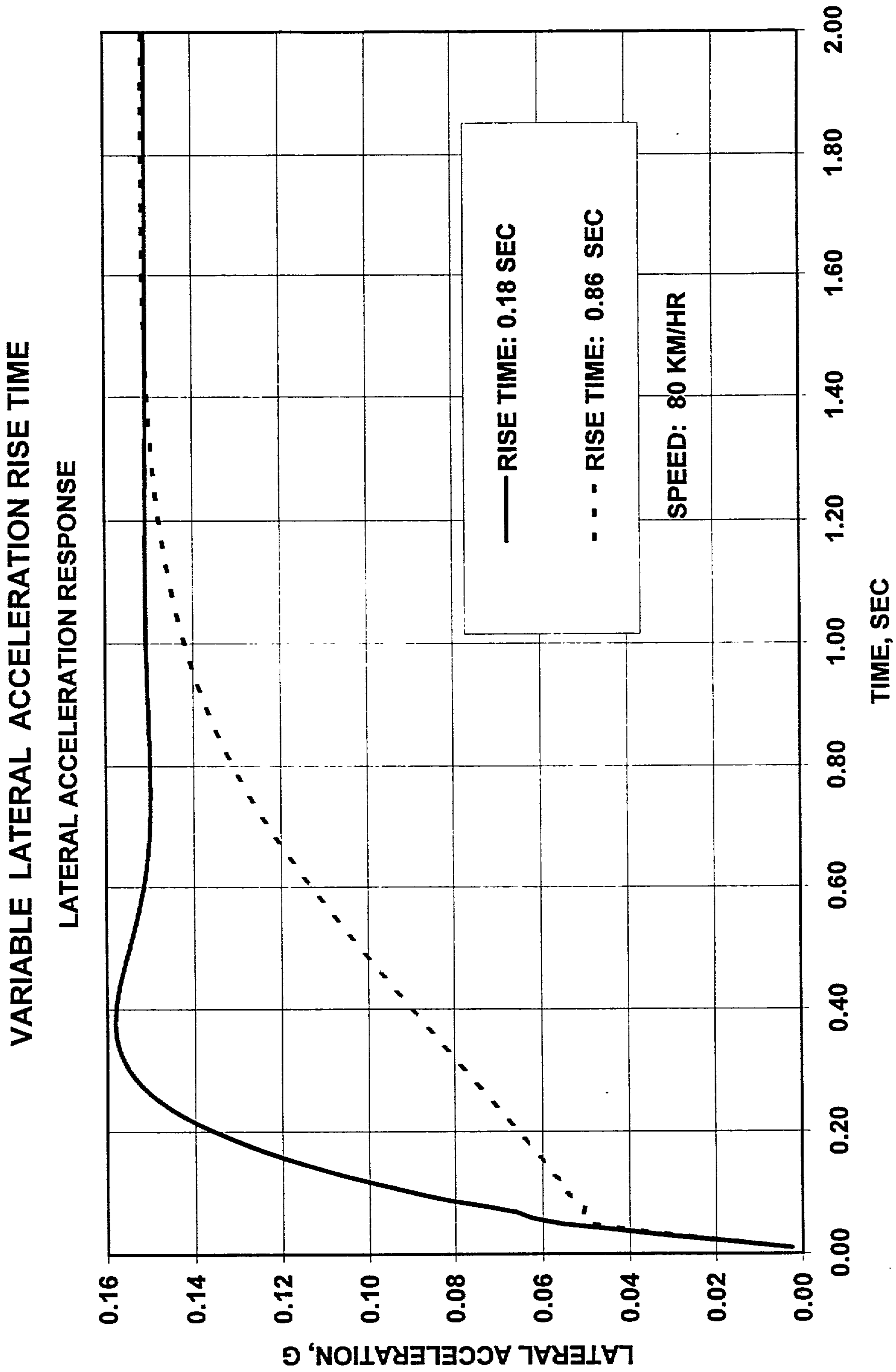
$$N_{\delta F} K_{FD\beta} + N_{\delta R} K_{RD\beta} = 0$$

(NO EXTRANEOUS ($d\beta/dt$) TERM IN YAWING MOMENT EQUATON)

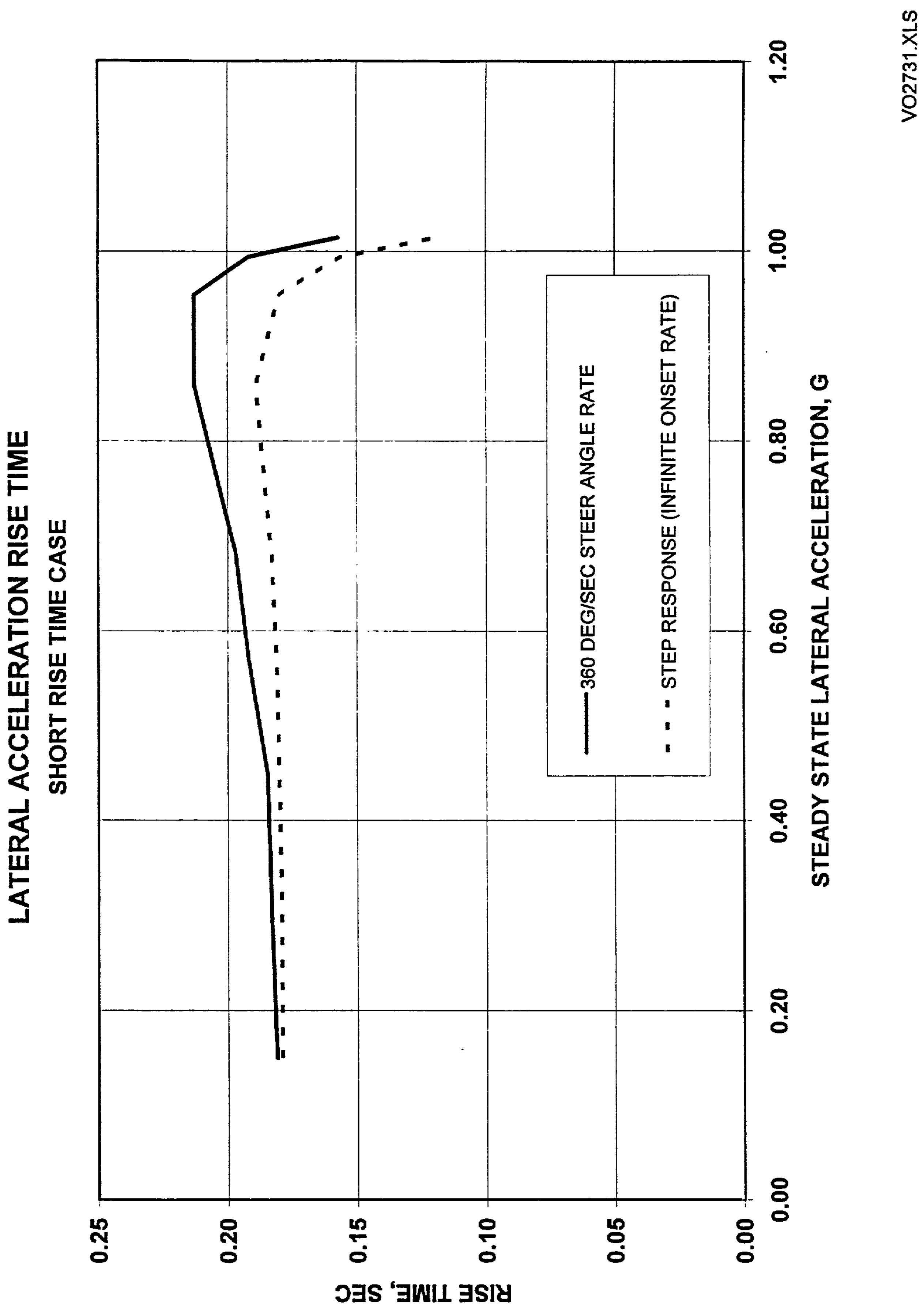
SIMULATION RUNS:

UNDERSTEER GRADIENT: 3.1 DEG/G
SPEED: 80 KM/HR
STEERING WHEEL RATE: 360 DEG/SEC,

$K_{FD\beta}$ SEC	$K_{RD\beta}$ SEC	K_{FDr} SEC	K_{RDr} SEC	I_Z' FT-LB-SEC	TIME TO 90% SEC	RISE TIME SEC
-0.2	-.080	0	0	2199	0.88	0.86
-0.2	-.080	-.04	.02726	13,200	0.20	0.18

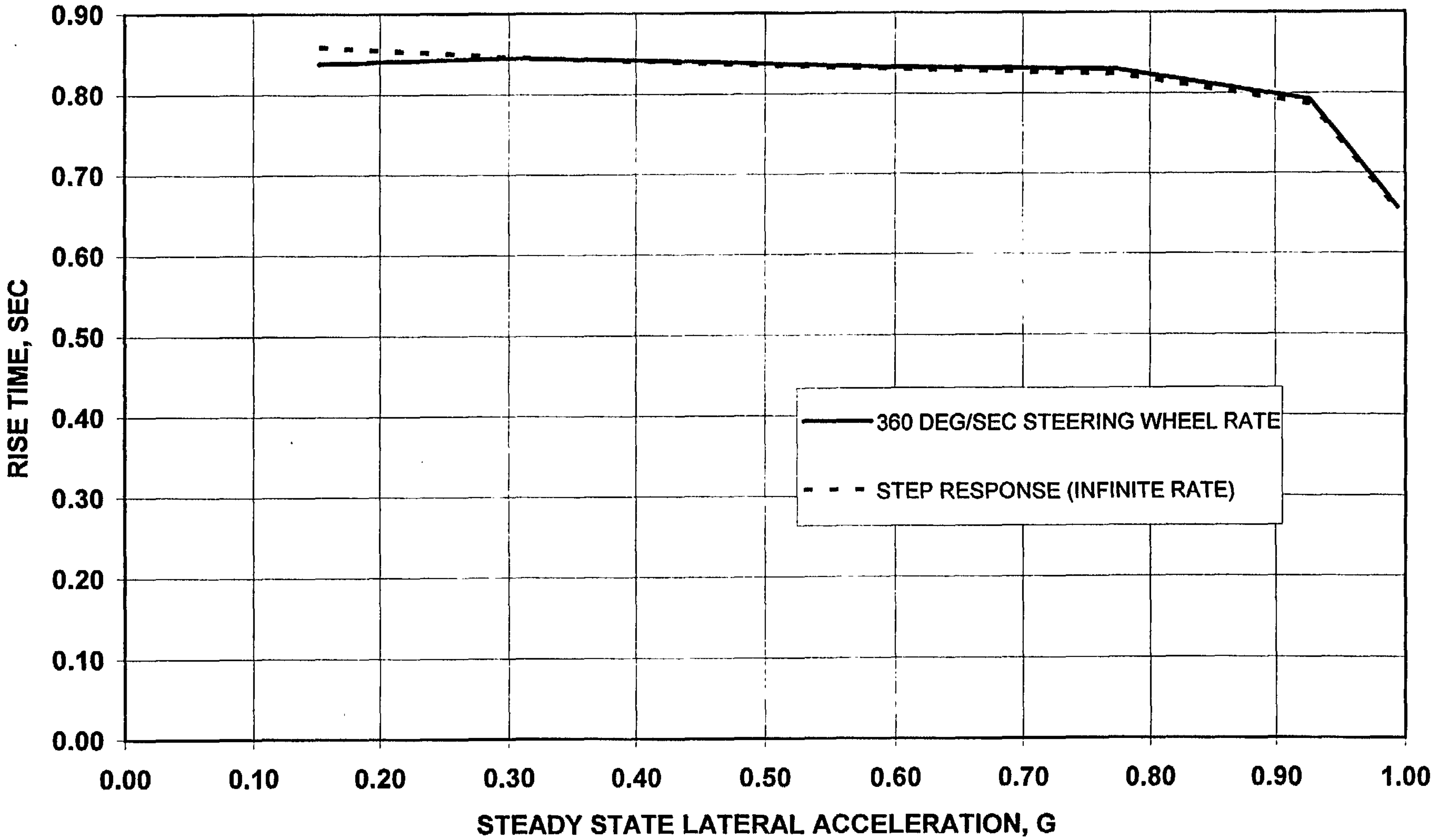


VARIABLE LATERAL ACCELERATION RISE TIME
LATERAL ACCELERATION RESPONSE
RISE TIME: 0.18 SEC
RISE TIME: 0.86 SEC
SPEED: 80 KM/HR
LATERAL ACCELERATION, G
0.16
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
TIME, SEC
0.00
0.20
0.40
0.60
0.80
1.00
1.20
1.40
1.60
1.80
2.00


LATERAL ACCELERATION RISE TIME
SHORT RISE TIME CASE
RISE TIME, SEC
0.25
0.20
0.15
0.10
0.05
0.00
STEADY STATE LATERAL ACCELERATION, G
0.00
0.20
0.40
0.60
0.80
1.00
1.20
360 DEG/SEC STEER ANGLE RATE
STEP RESPONSE (INFINITE ONSET RATE)
VO2731.XLS

LATERAL ACCELERATION RISE TIME

LONG RISE TIME CASE



VO2731.XLS

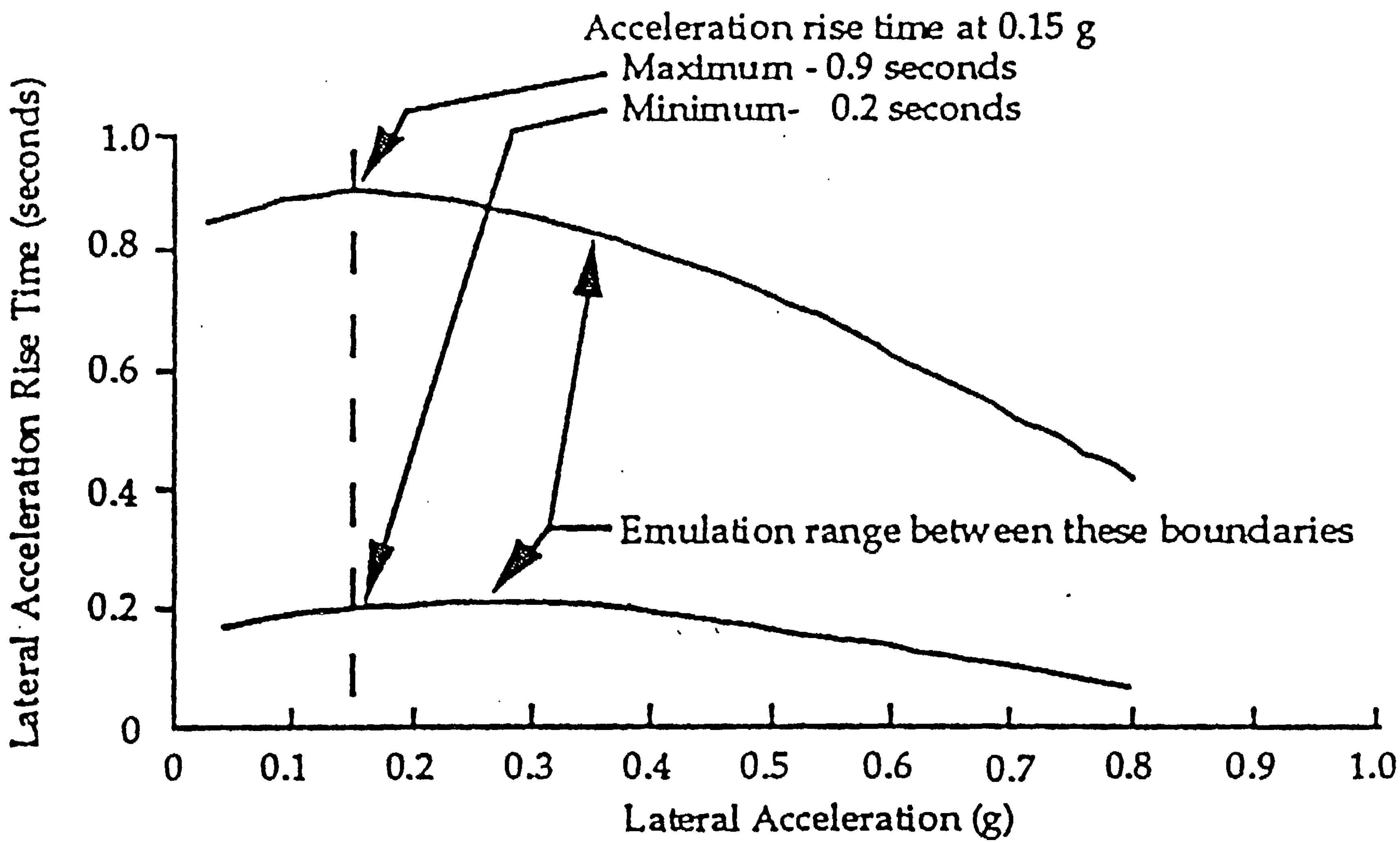
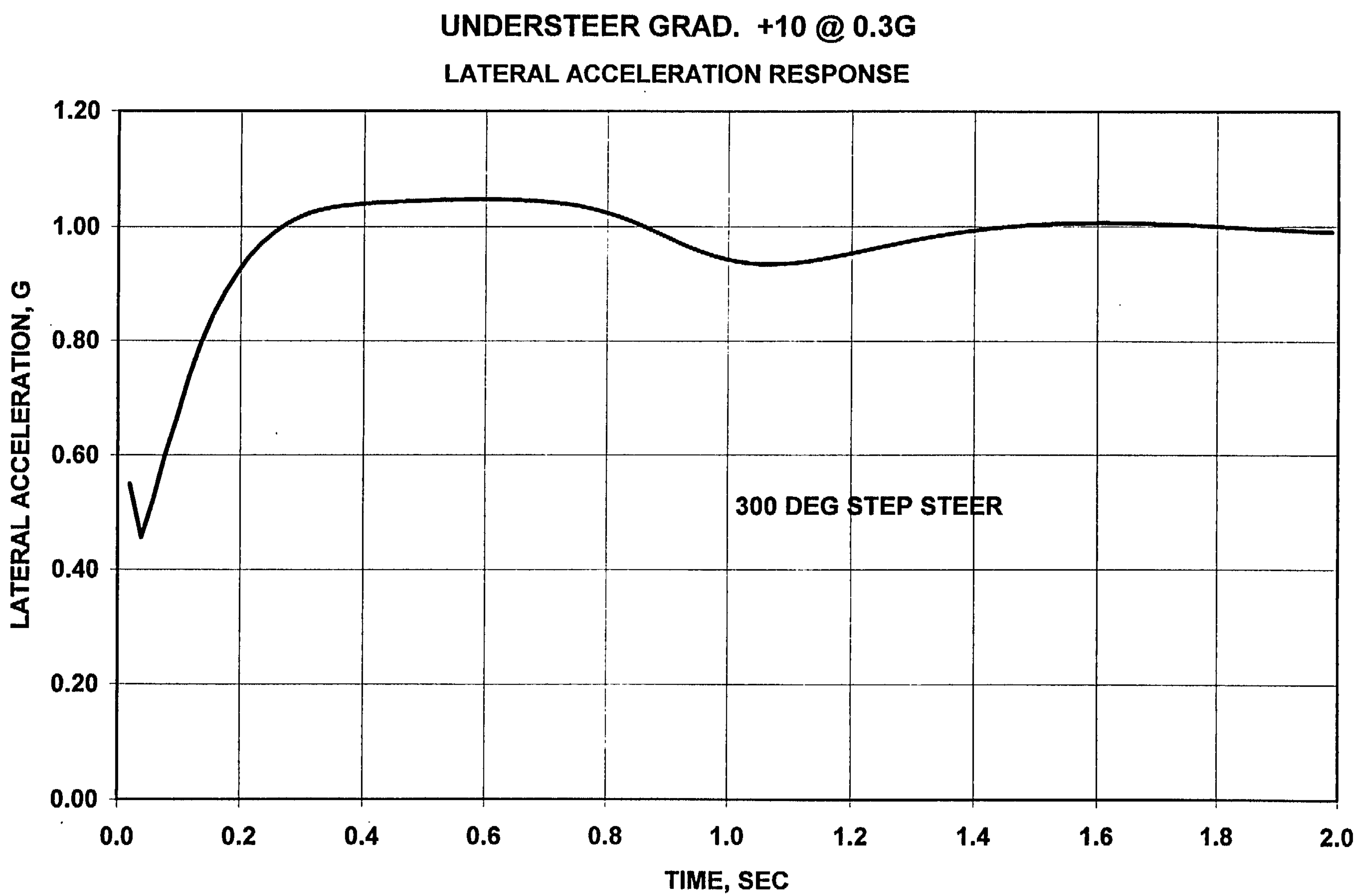
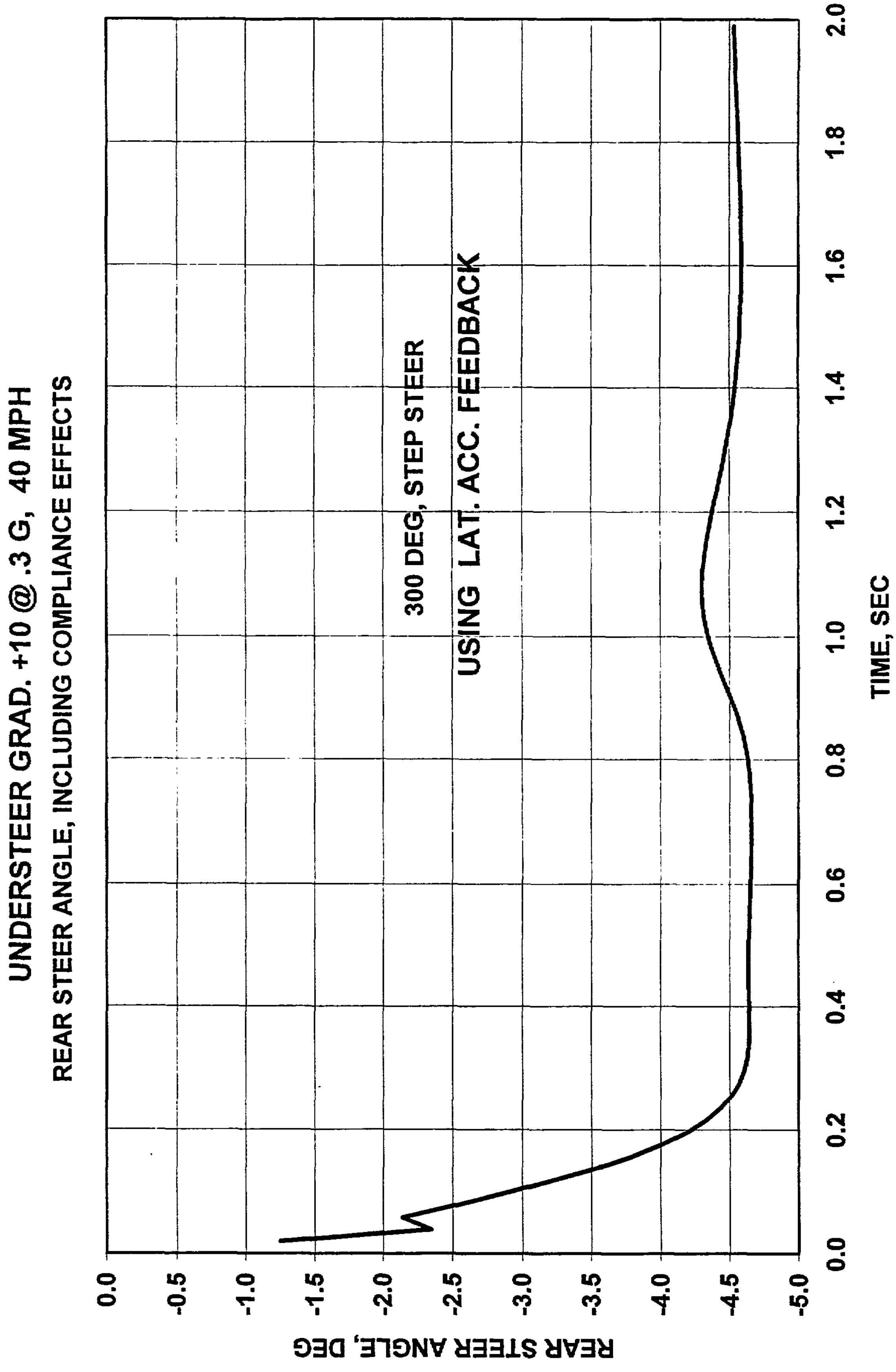
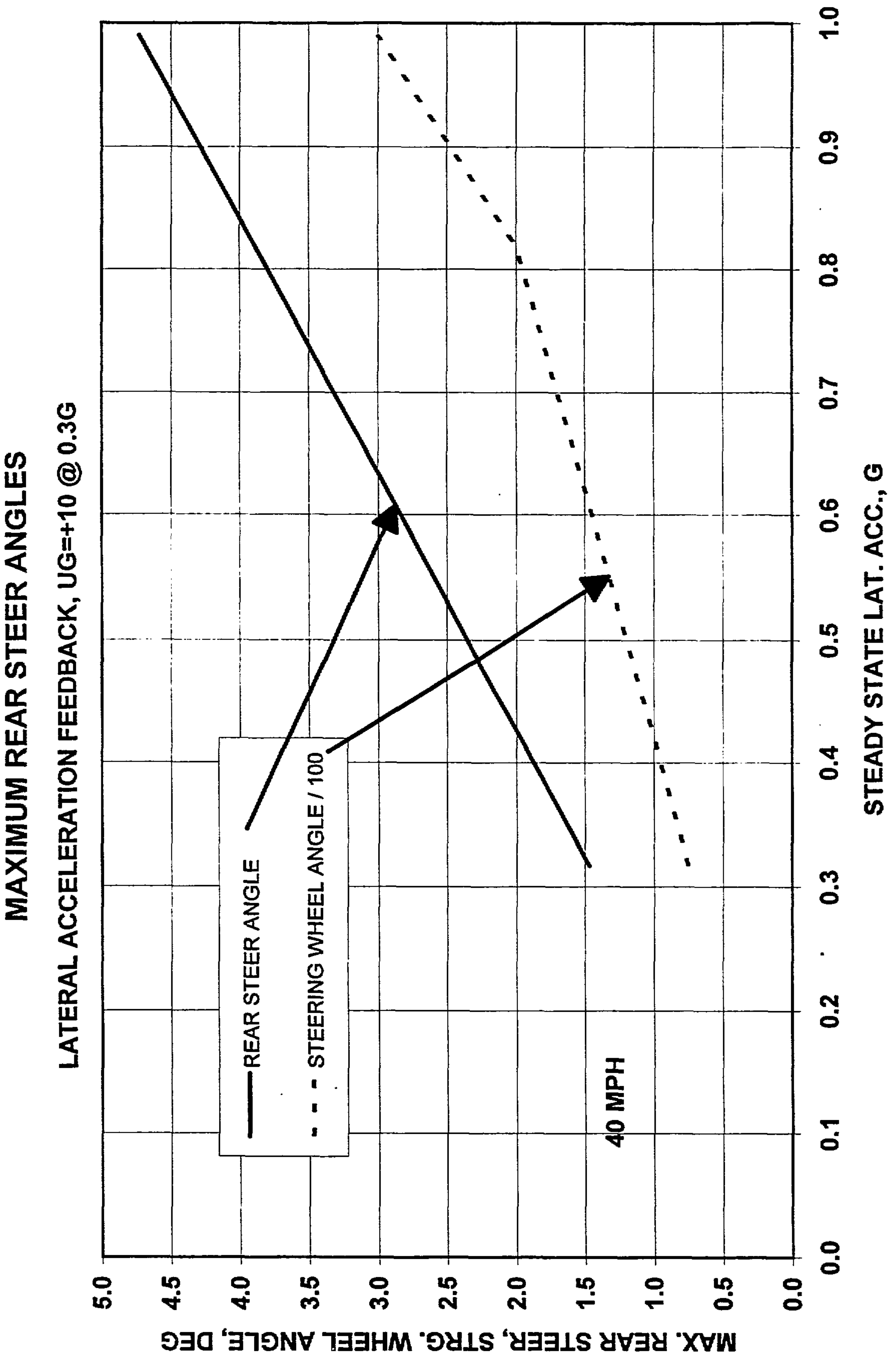


Figure 3-6. J Turn Lateral Acceleration Rise Time


UNDERSTEER GRAD. +10 @ 0.3G
LATERAL ACCELERATION RESPONSE
1.20
1.00
0.80
0.60
0.40
0.20
0.00
LATERAL ACCELERATION, G
300 DEG STEP STEER
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
TIME, SEC

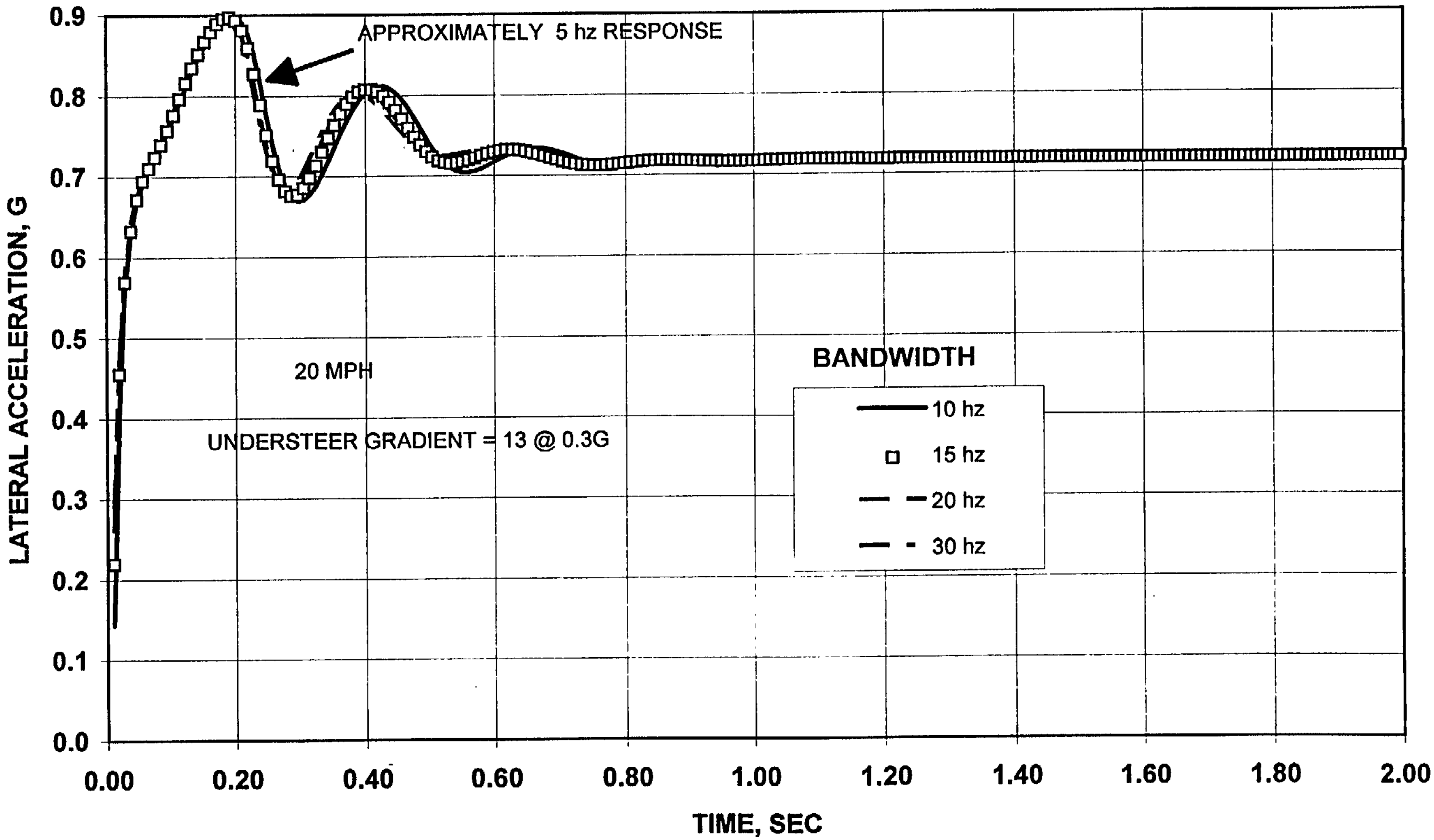

UNDERSTEER GRAD. +10 @ .3 G, 40 MPH
REAR STEER ANGLE, INCLUDING COMPLIANCE EFFECTS
300 DEG, STEP STEER
USING LAT. ACC. FEEDBACK
TIME, SEC
REAR STEER ANGLE, DEG
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
0.0
-0.5
-1.0
-1.5
-2.0
-2.5
-3.0
-3.5
-4.0
-4.5
-5.0

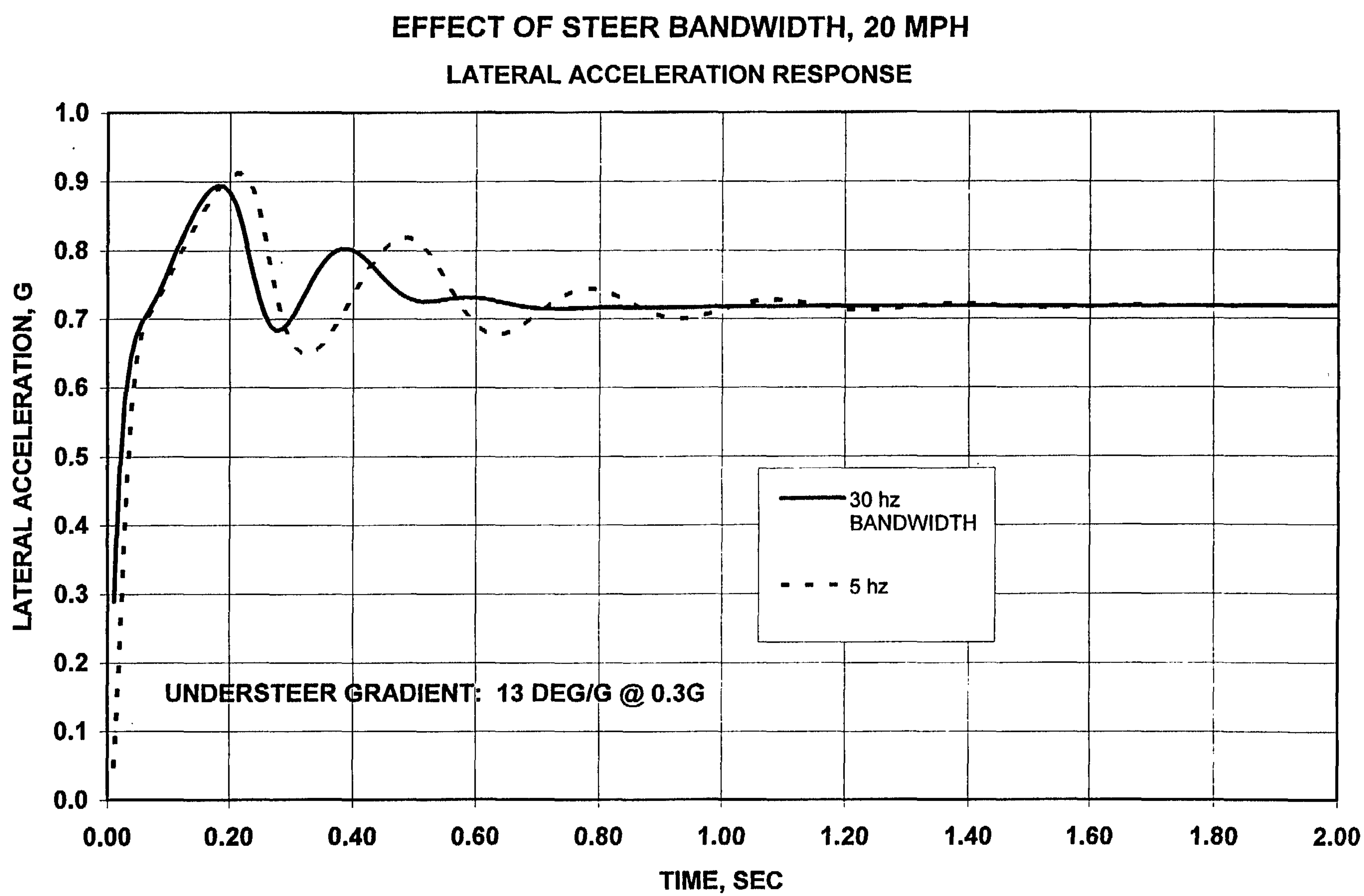


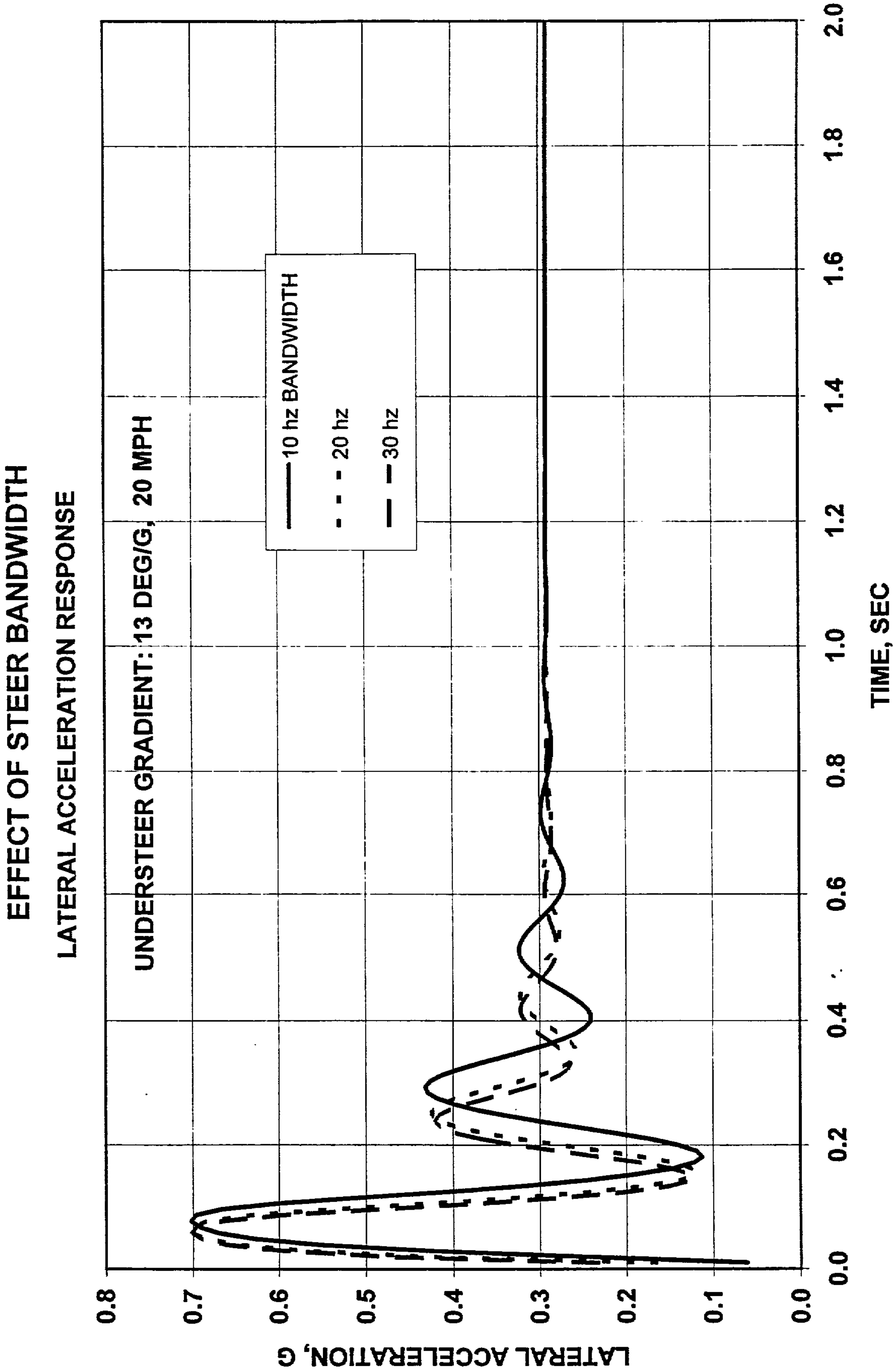
MAXIMUM REAR STEER ANGLES
LATERAL ACCELERATION FEEDBACK, UG=+10 @ 0.3G
REAR STEER ANGLE
STEERING WHEEL ANGLE / 100
40 MPH
MAX. REAR STEER, STRG. WHEEL ANGLE, DEG
STEADY STATE LAT. ACC., G
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0

EFFECT OF STEER SUBSYSTEM BANDWIDTH

LATERAL ACCELERATION RESPONSE




EFFECT OF STEER BANDWIDTH, 20 MPH
LATERAL ACCELERATION RESPONSE
LATERAL ACCELERATION, G
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0.00
0.20
0.40
0.60
0.80
1.00
1.20
1.40
1.60
1.80
2.00
TIME, SEC
30 hz BANDWIDTH
5 hz
UNDERSTEER GRADIENT: 13 DEG/G @ 0.3G


EFFECT OF STEER BANDWIDTH
LATERAL ACCELERATION RESPONSE
UNDERSTEER GRADIENT: 13 DEG/G, 20 MPH
10 hz BANDWIDTH
20 hz
30 hz
LATERAL ACCELERATION, G
TIME, SEC
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0

SUMMARY OF GOALS, REQUIREMENTS AN-D ANALYSIS RESULTS

Handling Metric	Goal per Fleet Data	Requirement per RFP	Analysis Result per Simulations
Understeer Gradient, deg/g @ 0.15g	-1 to + 9.0	-4 to +13	-4 to +13
Roll Gradient, deg/g	-12.5 to -1	-12.5 to -2.5	
Sideslip Angle Gradient, deg/g -50 mph	-5 to +l	NA	-5 to +4
Steering Torque Gradient, in-lbf/g	50 to 300	Specified in Terms of % Power Assist	—
Steering Torsional Stiffness, in-lbf/deg	0.3 @ 30 mph to 3.5 @ 75 mph	NA	-------

SUMMARY OF GOALS, REQUIREMENTS AND ANALYSIS RESULTS (cont'd.)

Handling Metric	Goal per Fleet Data	Requirement per RFP	Analysis Result per Simulations
Maximum Lateral Acceleration, g	0.4 to 1.0 (dry surface)	**0 to 0.95g** on 30m Circle	1.0 max
Steering Sensitivity, g per 100 deg, SWA Angle	.4 to 1.5 * @ 45 mph .4 to 2.2* @ 60 mph .4 to 2.4* @ 75 mph	NA	Fully Variable, Limited by Max. Steer Angle
Lateral Accel. -3db Bandwidth, hz	.6 to 2.0 @ 60 mph	NA	No Frequency Responses
Lateral Accel. 90% Rise Time, sec 0.15g, 80 km/hr	NA	0.2 to 0.9	0.22 to 0.89

* Maximum value increases with decreasing understeer gradient, e.g., infinite for oversteer, above critical speed.

SUMMARY OF GOALS, REQUIREMENTS AND ANALYSIS RESULTS (cont'd.)

Handling Metric	Goal per Fleet Data	Requirement per RFP	Analysis Result per Simulations
Yaw Rate Band -3db Bandwidth, hz	1.5 to 4.0 @ 25 mph 0.7 to 3.0 @ 50 mph	NA	-------
Percent Overshoot in Yaw Rate	0 to 40% (50 mph) 0 to 100%# (75 mph)	NA	2% to 58%
Time to Peak Yaw Rate Response, sec (.4g, 50 mph)	0.2 to 0.9	NA	0.22 to 0.89
Roll Angle Bandwidth, hz	0.8 to 4.8 (25 mph) 0.3 to 1.5 (50 mph)	NA	TBD

Corresponds to high understeer gradient and low damping.

STEER SUBSYSTEM FEEDBACKS

Feedback Variable: Front Steer	Feedback Variable: Rear **Steer**	Used to Vary
Sideslip Angle	Sideslip Angle	Understeer (75 mph) Acceleration Rise Time (80 km/hr)
Sideslip Angle Yaw Rate		Understeer (varying speed) & Amplitude
Sideslip Rate Yaw Accel.	Sideslip Rate Yaw Accel.	Percent Overshoot in Yaw Response Time to Peak Yaw Rate Response. Acceleration Rise Time (80 km/hr)
Yaw Rate	------	Understeer (40 mph)
Lateral Accel.	Lateral Accel.	Understeer (40 mph) Understeer (75 mph)
Roll Angle	Roll Angle	Roll Decoupling from Yaw/Sideslip
Roll Accel.	Roll Accel.	Roll Decoupling from Yaw/Sideslip
Steering Wheel Ang.		All Cases
	Steering Wheel Ang.	Steady State Sideslip Response (Trial Cases, not to Satisfy Goals)
	Front Wheel Angle	Sideslip, Yaw Rate Response (Trial Cases, not to Satisfy Goals)

SUMMARY

STEER SUBSYSTEM:

- 0 REDUCE FRICTION, USE STEER DAMPER, FEEDBACK WHEEL POSITION AND RATE
- 0 20 hz BANDWIDTH PRACTICAL WITH REASONABLE DAMPING
- 0 20 hz BANDWIDTH ADEQUATE FOR STRESSING RESPONSE CONDITIONS
- 0 4 DEG REAR STEER REQUIRED FOR VERY STRESSING RESPONSE CONDITIONS

CONTROL CAPABILITY

- 0 UNDERSTEER GRADIENT RANGE MEETS REQUIREMENTS AT 0.15G

- 0 LATERAL ACCELERATION RISE TIMES MEET REQUIREMENTS OVER RANGE OF STEADY STATE LATERAL ACCELERATIONS

- 0 YAW RATE OVERSHOOT AND TIMES TO PEAK MEET GOALS

- 0 STEER SENSITIVITY LIMITED ONLY BY FRONT WHEEL STEER ANGLE

- 0 MAXIMUM LATERAL ACCELERATION > 1G WITH ZR TIRES

* CAN BE REDUCED BY NONLINEAR STEERING RATIO VS LATERAL ACCELERATION

5.0 Subsystem Requirements

5.1 Overview

This section covers the flow down of vehicle-level requirements to the individual subsystems. In general, this document assumes compliance with Exhibit L Deviations and additions to the Exhibit I requirements will be discussed in the following paragraphs. All document section references refer to Exhibit L Except where noted, this section reflects the state of the system architecture and functionality as of December 5, 1996.

5.2 Overall Control

An overall control bandwidth requirement of 20 Hz exists. To satisfy the standard 10 to 1 ratio of controller time rate to system bandwidth, sensor sampling rates and actuator update rates of 200 Hz are required. This translates into a 5-millisecond period per subsystem. In the case of the steering feel system, empirical experience indicates that a sampling and control rate of at least 500 Hz is required (2-millisecond period). The implications to the various subsystems are as follows.

5 . 3 Electronics

In general, all of the VDTV electronics have to meet the following requirements. Except for embedded electronics, any element must be removable within 15 minutes. Also, electronics must operate with ambient conditions from -20 deg C to 38 deg C (assuming interior temperature ranges from 20 deg C to 32 deg C after warm-up/cool down). Electromagnetic compatibility to an electric-field strength of 100 V/meter is also required.

5.4 Control Computer

5.4.1 General

In general, the control computer will meet all of the requirements of Exhibit I, Section 4.4. The control computer will accept IBM PC-compatible 3.5inch floppy media. The control computer must maintain configuration information as specified in Section 3.5.1 1.3, Sensor Configuration. It will also monitor all electrical system voltage levels. It must be of sufficient processing power to support the closed-loop control described previously. The control computer will transfer all data to the Measurement Subsystem (MS/S) via the J1939 data bus. Data transfer to the MS/S will conform to Section 4.4.11.

5.4.2 Vehicle Control

The control computer has seven separate control loops (per rescope): front steering, rear steering, steering feel, braking, throttle, roll control, and semi-active suspension. Note that the antilock braking system (ABS) is embedded into the Delphi electronic control unit (ECU). Also note that computer control of brake and throttle feel have been deleted per rescope. Each control loop is 5 milliseconds as described above, except steering feel, which is 2 milliseconds. The control computer must be capable of meeting these cycle times.

5.4.3 Software

The software will adhere to the requirements of Section 4.4.5 in Exhibit I. The control algorithms described in Section 4.4.6 of Exhibit I will be hosted primarily on the control computer. However, low-level, direct control of the individual subsystems will be controlled by their corresponding vendor-supplied ECU. The control computer will contain the support for user-supplied algorithms described in Section 4.4.6.2.

5.4.4 Safety

The control computer must generate a system health and status (SHS) message every 10 milliseconds. The real-time monitoring outlined in Section 4.4.1.2 will be done via this message. Also, the SHS must observe all safety critical control and sensor information for out-of-range numbers every 10 milliseconds per Section 4.4.1.2 (b), and check data slope of critical items to identify unsafe operation per Section 4.4.1.2 (c). The control computer will indicate failures (per Section 4.4.1.2) and instruct the watchdog module to engage mechanical backups where appropriate. Safety critical data must be checked before usage by control algorithms (per Section 4.4.1.2).

5.4.5 Performance Verification Test (PVT)

The control computer must store and issue the time series of control commands to perform the maneuvers defined in Section 3.5.1.1. The computer will compare the actual results witb the upper and lower performance bounds and issue a health message within 30 seconds.

5.5 Critical Data Items

The critical data items are those items of sensor data and actuator commands that affect the safety of the vehicle. All of the items listed under "Dynamic Subsystems,'* "Power S/S," and "Body Motions" in Table 4-l of Exhibit 1 that are listed as safety critical items (SCI) are considered critical data items. Items under "User-Supplied Equipment" must be assessed on a case-by-case basis. Only information from the vehicle subsystems being controlled will be monitored electronically. These items will be inspected every 10 milliseconds during the safety check, and any actuator commands that affect these items will be tested before being applied to the actuator. Key items for identifying the current dynamic state of the vehicle are:

1. Vehicle velocity (longitudinal)
2. Longitudinal acceleration
3. Lateral velocity
4. Lateral acceleration
5. Yaw velocity
6. Yaw acceleration

7. Body roll
8. Front-rack position
9. Rear-rack position

Obviously, several of these items are derived quantities and are the result of both the situational dynamics and the actuator actions.

5.6 Graphical User interface (GUI)

The GUI will be the principal means of interacting with the vehicle electronics (excluding the MS/S) and will have the capabilities described in Section 4.4.9. The various PVTs will be invoked from the GUI, which will also report the PVT results. The GUI will handle updates of desired dynamic performance or control coefficients from the keyboard or floppy media, and it will also handle updates of control algorithms from floppy media. The GUI will display system health and status on a continuing basis. Any data limit failures outlined in Section 4.4.1.2 (b) iii and (c) iii will also be displayed.

5.7 *Sensors*

Note that in most instances the sensors required will be embedded in the various dynamic subsystems.

The sensors shown on the following page have been identified by Milliken Research Associates (MRA) through its analysis or are called out in Exhibit I (excluding Table 4.1).

Sensor	Bandwidth	Accuracy	Range	Resolution
	(Hz)			
Lateral Acceleration	20			
Front Rack Position	20	0.02 deg.		
Steering Wheel Position	20			
Steering Wheel Angle	20			
Longitudinal Acceleration	20			0.01 g
Vehicle Velocity	20			
Yaw Acceleration	20			
Yaw Velocity	20			
Wheel Motion -- Vertical	20			
Voltmeters	NA			
Roll Angle	20			
Roll Acceleration	20			
Slideslip Angle	20			

This sensor list is not meant to be exhaustive, but represents those sensors specifically identified by MRA analysis or referenced in Exhibit I.

5.8 Front Steer-by-Wire

This dynamic subsystem will perform according to Exhibit I, Section 4.3.1. MRA has made several recommendations to maximize the actual frequency response of the system. These include:

1. Minimize steer mode friction
2. Add viscous damper on steer angle
3. Minimize steer mode compliances
4. Add steer-angle feedback
5. Measure or calculate slideslip angle, lateral acceleration, and yaw acceleration/rate to control understeer, acceleration rise time, percent overshoot in yaw response, and time-to-peak yaw response

5.9 Rear Steer-by- Wire

This dynamic subsystem will perform according to Exhibit I, Section 4.3.7.

5.10 Steering Feel

This dynamic subsystem will perform according to Exhibit I, Section 4.3.2.

5.7 1 Brake-by-Wire

This dynamic subsystem will perform according to Exhibit I, Section 4.3.3. However, the minimum deceleration of 0.005 g is not obtainable while maintaining Federal Motor Vehicle Safety Standards (FMVSS) braking requirements. This is according to GM-Delphi analysis.

5.12 *Brake Feel*

This dynamic subsystem will perform according to Exhibit I, Section 4.3.4. However, per the rescope effort, Section 4.3.4 is being modifii to allow mechanically adjustable brake feel. The feel emulation ranges will cover the range that GM-Delphi has demonstrated to fully represent passenger vehicles. Per the rescope, driver attention pulses will not be delivered to the pedal; instead, the brakes will be applied to achieve the driver warning effect d&red.

5.13 Automatic Braking System

This dynamic subsystem will perform according to Exhibit I, Section 4.3.9. However, there will not be individual wheel slip ratio control from the laptop computer. Yaw control and traction control algorithms from GM-Delphi will be available and selectable from the control computer.

5.14 Throttle-by-Wire

This dynamic subsystem will perform according to Exhibit I, Section 4.3.5.

5.15 Throttle Feel

This dynamic subsystem will perform according to Exhibit I, Section 4.3.6. However, per the rescope, throttle feel will be mechanically based and not electronically controlled.

5.16 Semi-Active Suspension

This dynamic subsystem will perform according to Exhibit I, Section 4.3.8.

5.17 Roll Control

This dynamic subsystem will perform according to Exhibit I, Section 7.1.2. MRA has recommended that the system measure roll angle and roll acceleration to enable the decoupling of roll from yaw/slideslip.

5.18 Subsystem interface Modules

These modules must provide CAN interface to the system control bus. They will be 51939 compliant (250 kilobits per second). These modules also must provide the digital and analog interface to the dynamic subsystems and control computer.

5.79 Watchdog Module

The primary purpose of the watchdog module is to provide safety. The module protects the VDTV from a single-point fault causing a system failure that cannot be resolved safely. The module observes system health and status (SHS) messages generated by the control computer and acts on failure reports and lack of SHS message. The watchdog module generates a status message on its health every 10 milliseconds, a message for which the control computer is watching. If the watchdog module is not fully functional, then the control computer will notify the driver.

The module has control of the electro-mechanical relays for each of the mechanical backup systems. The backups are positively disengaged, i.e., default is engaged. A power failure to either the watchdog module or the control computer results in all of the backups engaging. A failure in a single dynamic subsystem will cause the watchdog module to engage the appropriate mechanical backup. The watchdog module and the control computer will signal occupants of any failures.

5.20 Mechanical Backups

Must be engaged electronically within 50 milliseconds after a failure detection.

5.21 Testing

5.21.1 Sensors

Most sensors will be redundant on the vehicle. Therefore, sensor values will be compared to assess functionality. For critical/nonredundant sensors, a temporary sensor suite will be added to assess functionality. One option for precision motion measurement is the ERIM MMS (Motion Measurement System), which utilizes the Honeywell Precision Inertial Measurement Unit to achieve centimeter level accuracy in even high dynamics maneuvering. Another option is a high accuracy GPS unit capable of tracking under high dynamics, such as the Ashtech 212.

5.21.2 CAN Bus

A vehicle-level bus communication test tool will be used for testing. This tool must be able to record all message traffic, similar to a flight recorder function, and the data must be recorded with a time stamp. The tool will be used to asses bus latency and closed-loop control feedback The tool must be able to filter messages to focus on specific communications. Our plan is to use an off-the-shelf bus monitor. Tools from Softing, I+ME, Tnet, the Dearborn Group, and Parasoft are under consideration. The tool needs to be selected by April 1, 1997.

5.21.3 Vehicle Dynamics

To verify vehicle dynamics, our primary approach will be to use a precision motion measurement instrument. Again, one option is the ERIM MMS. Another option is a high-accuracy global positioning system (GPS) unit capable of tracking under high dynamics, such as the Ashtech 212.

5.22 User-Supplied Equipment (USE)

There will be four interface points on the VDTV: front, rear, and both sides. The interface points will adhere to the description presented in Exhibit I, Section 4.8.2.1. The data interface to the USE will be via an independent CAN bus. The power interface will provide the following to each interface point:

1. +/- 12 volts @ 1 amp
2. 5 volts @ 0.5 amp

5.23 Mechanical Subsystem

The mechanical subsystem will conform to Exhibit I, Section 4.5 except for Section 4.5.1.3. There will be no requirement for airbags in the VDTV.

5.24 Electrical *Power*

This subsystem will conform to Exhibit I, Section 4.6. The only deviation required is to strike Section 4.6.4 (e).

APPENDIX A

MILLIKEN RESEARCH ASSOCIATES
VARIABLE DYNAMIC TEST VEHICLE
PROGRESS REPORT FOR OCTOBER, 1996

To: Dave McLellan, Janet Nyman (ERlM)
From: H. S. Radt and S. A. Radt
Cc: W. F. Milliken
Date: October 30, 1996

VDTV FEEDBACK CONTROL ANALYSIS AND SIMULATION

1. Closed Form Analyses:

MRA is initially concerned with lateral accelerations less than 0.3g so that linear analysis applies within the limitations of control dynamics, tire lags and compliance external to the steer control subsystems. We first decouple the roll degree of freedom from the yaw-sideslip degrees of freedom, then analyze the yaw-sideslip mode as a simple two degree-of-freedom system. The general approach following decoupling of roll is to define several response characteristics of the yaw sideslip mode, such as natural frequency, damping, numerator time constants, understeer gradient, steering sensitivity, etc., all in terms of stability derivatives. We then modify these stability derivatives via feedback of responses such as sideslip angle and rate; yaw rate and yaw acceleration; roll angle, rate and acceleration; lateral acceleration and front steer angle or steering wheel angle.

This approach has been demonstrated for roll decoupling, including effects of control and tire dynamics, with and without front steer compliance. It has also been shown to work effectively in changing the yaw-sideslip damping when the natural frequency is left unchanged. However, attempts to change frequency and damping independently, using the closed form analysis, did not produce simulation results that showed the desired changes. Accordingly, we have reverted to a calibration approach wherein systematic changes were made in the individual gains to "map" changes in overshoot and rise time.

2. Simulation Results:

Simulations to date have used tire data supplied by Goodyear for a P275/40ZR-16 tire. These data appear to show a camber trail (self aligning torque due to camber divided by camber stiffness) which is 5 to 10 times larger than data we previously obtained on normal passenger car tires. The resulting high value of self aligning torque couples with front steer compliance to produce major effects on the VDTV understeer gradient. When front steer compliance is assumed zero, the baseline VDTV is calculated to be nearly neutrally stable.

We have evaluated roll decoupling and found that the roll frequency and damping can be modified over wide ranges, while the yaw rate response remains essentially unchanged. After decoupling, we evaluated effects of front steer proportional to yaw rate. Variations in this gain produced major changes in understeer gradient. The effective steering ratio was varied to maintain the value of the steering sensitivity. High values of understeer gradient, e.g. 6 to 10 deg/g, resulted in oscillatory responses in yaw and lateral acceleration. Decreased damping is a typical result of increasing understeer gradient for passenger cars, but is not as pronounced as occurs for excessive gradients as high as 10 deg/g.

We have attempted to eliminate such oscillations so that we can achieve short rise times with reduced overshoot and improved stability for the high understeer gradients. One unsuccessful attempt consisted of feed forward of steering wheel angle to rear steer - adjusted to achieve zero steady state sideslip angle. However, zero steady state sideslip does not reduce the transient sideslip sufficiently to eliminate the oscillations in the response. We were successful in employing yaw acceleration to eliminate the oscillations, however, increased damping of these yaw-sideslip mode via yaw acceleration feedback results in longer rise times.

Currently we a searching for a feedback variable that will eliminate oscillatory behavior at large values of understeer gradient, while maintaining short rise times of the order of 0.05 to 0.10 sec. Feedback of rate of change of sideslip appears to be promising. Appropriate use of rear steer from yaw rate may also be helpful.

We have also determined effects of front and rear steer control subsystem bandwidth (70% critical damping) for simple models of these subsystems. For nominal understeer gradients of 1 to 5 deg/g, the value of 15 hz, specified in the VDTV RFP appears acceptable. That is, there is little effect on yaw and lateral acceleration responses. However, 15 hz is a rather narrow bandwidth when one tries to achieve understeer gradients as high as 10 deg/g or higher. We have by no means exhausted potential techniques for compensating for control lags, e.g., compensation with a lead-lag network or use of additional feedbacks. Changing of tire pressures or using different tires front and rear could be used to make the VDTV more understeer, thereby making it “easier” to increase understeer to high values. That is, lower gain values would be needed to achieve the higher understeer gradients.

Effects of front steer compliance and tire lags have also been assessed. Further simulations are required to define acceptable boundaries. In doing so we have to arrive at a reasonable range of desired understeer gradients and appropriate operating procedures, .e.g., with or without tire changes.

Simulations completed to date indicate that very small rear steer angles are required, e.g., less than one degree. However, we have been using rear steer primarily in decoupling the roll degree-of-freedom. When using rear steer proportional to yaw rate, etc. we may find that larger angles are needed. We have not set limits on steer angle rates, but thus far the required rates appear to be relatively low.

3. Future Effort on Simulations and Analysis:

MRA will meet with MDI, ERIM and TRW to share results to date and to discuss critical design parameters that can be assessed using the simulations, e.g., steer angle rate, steer subsystem bandwidth, front steer compliance and maximum rear steer angle.

We plan to perform simulations using various additional feedback variables to determine the “ultimate” capability of VDTV .

As more accurate data become available on the modified Taurus SHO, we will update the input parameters of the simulation. Examples are masses, moments and product of inertia, compliances, center of gravity positions, any changes in roll center heights, etc. If additional tire data become available we will upgrade our tire data inputs as well.

MRA will report to ERIM anticipated maximum performance of VDTV for various conditions (e.g., speed, tires, etc.) in terms of the various metrics (e.g., understeer gradient, steering sensitivity, yaw rate and lateral acceleration rise time, roll gradient, etc.)

4. US Fleet Metric Data:

MRA has tabulated data from Ford on about 27 passenger cars and station wagons. Included are: wheelbase, weight, yaw gain, steering torque gradient and gain, steering sensitivity, yaw rate overshoot, understeer gradient, and roll gradient. Frequency response data include: lateral acceleration bandwidth at three speeds, roll angle and yaw rate peak frequencies and frequency at 45 degrees of phase lag, and ratio of peak magnitude to steady state for the yaw rate. Some of these data have been summarized for maxima, minima, average and standard deviation.

5. Future Effort on US Fleet Metric Data:

MRA will complete summaries of the Ford metric data. Similar analyses will be performed on data to be obtained from GM, if available in time.

From the Ford, GM and NHTSA data we will make recommendations to ERIM regarding suitable goals for response metrics such as those listed above. Included will be maximum and minimum values, where appropriate.